The Rotation of Surviving Companion Stars after Type Ia Supernova Explosions in the WD+MS Scenario

Zheng-Wei. Liu1,2,3,4, R. Pakmor5,4, F. K. Röpke6,4, P. Edelmann4, W. Hillebrandt4, W. E. Kerzendorf7,8, B. Wang1,2 and Z. W. Han1,2

1 National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, P.R. China
2 Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, P.R. China
3 University of Chinese Academy of Sciences, Beijing 100049, P.R. China
4 Max-Planck-Institute für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
5 e-mail: zwliu@ynao.ac.cn
6 Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, 69118 Heidelberg, Germany
7 Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
8 Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston Creek, ACT 2611, Australia
9 Department of Astronomy and Astrophysics, University of Toronto, 50 Saint George Street, Toronto, ON M5S 3H4, Canada

Preprint online version: February 6, 2014

ABSTRACT

Context. In the single degenerate (SD) scenario of type Ia supernovae (SNe Ia) the non-degenerate companion star survives the supernova (SN) explosion and thus should be visible near the center of the SN remnant and may show some unusual features. Therefore, a promising approach to test progenitor models of SNe Ia is to search for the companion star in historical SN remnants.

Aims. Here we present the results of three-dimensional (3D) hydrodynamics simulations of the interaction between the SN Ia blast wave and a MS companion taking into consideration its orbital motion and spin. The primary goal of this work is to investigate the rotation of surviving companion stars after SN Ia explosions in the WD+MS scenario.

Methods. We use Eggleton’s stellar evolution code including the optically thick accretion wind model to obtain realistic models of companion stars. The impact of the supernova blast wave on these companion stars is followed in 3D hydrodynamic simulations employing the smoothed particle hydrodynamics (SPH) code GADGET3.

Results. We find that the rotation of the companion star does not significantly affect the amount of stripped mass and the kick velocity caused by the SN impact. However, in our simulations, the rotational velocity of the companion star is significantly reduced to about 14% to 32% of its pre-explosion value due to the expansion of the companion and the fact that 55% – 89% of the initial angular momentum is carried away by the stripped matter.

Conclusions. Compared with the observed rotational velocity of the presumed companion star of Tycho’s supernova, Tycho G, of \( \sim 6 \text{ km s}^{-1} \) the final rotational velocity we obtain in our simulations is still higher by at least a factor of two. Whether or no this difference is significant, and may cast doubts on the suggestion that Tycho G is the companion of SN 1572, has to be investigated in future studies. Based on binary population synthesis results we present, for the first time, the expected distribution of rotational velocities of companion stars after the SN explosion which may provide useful information for the identification of the surviving companion in observational searches in other historical SN remnants.

Key words. stars: rotation-supernovae: general-hydrodynamics-binaries: close

1. Introduction

Type Ia SNe (SNe Ia) are used as cosmic distance indicators since their luminosity can be calibrated based on the empirical relation between light curve shape and peak luminosity (Phillips, 1993; Phillips et al, 1999). This has provided the first evidence for the accelerating expansion of the present universe (Riess et al, 1998; Perlmutter et al, 1999; Leibundgut, 2008). SNe Ia are also believed to be important contributors to the cosmic nucleosynthesis and they are sources of kinetic energy in evolution process of galaxies. Although a detailed understanding of the nature of their progenitors and the physics of explosion is still lacking (Hillebrandt & Niemeyer, 2000 for a review), there is consensus that SNe Ia arise from thermonuclear explosions of carbon/oxygen white dwarfs (CO WDs) in binary systems (Hoyle & Fowler, 1960; Nomoto et al, 1997).

In principle, there are various possibilities for the evolution towards an explosion (see Wang & Han, 2012 for a review). One option is a merger of two CO WDs with a combined mass in excess of the Chandrasekhar mass, which may explode as a SN Ia, the ‘double degenerate’ (DD) scenario (Iben & Tutukov, 1984; Webbink, 1984). The DD model can explain in a natural way the lack of hydrogen in SNe Ia. However, only a few DD systems have been found whose orbital period is short enough that they will merge within a Hubble time, but in none of them the combined mass exceeds the Chandrasekhar mass limit. On the other hand, in recent numerical simulations of Pakmor et al (2010, 2011) it was found that the violent merger of a pair of white dwarfs with equal masses of \( \sim 0.9 \text{ M}_\odot \) can directly trigger a thermonuclear explosion that resembles sub-luminous 1991bg-like SNe Ia. Moreover, it was shown that the violent merger of two CO WDs with masses of \( 0.9 \text{ M}_\odot \) and \( 1.1 \text{ M}_\odot \) produces lightcurves and spectra which are in good agreement with those.
of normal SNe Ia \citep{Pakmor2012b}, supporting the DD scenario.

On the other hand, a rather massive WD may accrete hydrogen-rich material from a non-degenerate binary companion until it approaches the Chandrasekhar mass, the ‘single degenerate’ (SD) scenario. In this case, the binary companion could be a main-sequence (MS) star (WD+MS channel), a slightly evolved subgiant star or a red-giant (RG) star \citep{HanPodsiadlowski2003, WangHua2010b}. The lack of hydrogen in observed SN Ia spectra can be seen as troublesome for the SD scenario since the companions are hydrogen-rich stars. With more realistic MS companion star models than those used in previous work, \cite{Liu2012} performed three-dimensional (3D) smooth particle hydrodynamics (SPH) simulations of the interaction between SN Ia ejecta and the MS companion star. They found that in all cases they considered more than 0.1M$_\odot$ was stripped from the hydrogen-rich companion and was mixed into the SN ejecta, which is in disagreement with most recent observational constraints on the presence of hydrogen in SN Ia from nebular spectra $\sim 0.01$M$_\odot$ \citep{Leonard2007, Shanpee2013}. Moreover, no other similar hydrodynamics simulations showed an amount of stripped mass below this strong observational limit \citep[see][]{Marietta2000, Pakmor2008, Pan2010, Rickere2014, Pan2012b}. On the other hand, there is evidence from observations that the progenitors of at least some SNe Ia come from the SD channel. For instance, evidence for the presence of circumstellar matter and features indicative for an interaction between the SN and circumstellar matter were found recently \citep{Patata2007, Sternberg2011, Foley2012, Dildav2012}.

The merger of two WDs leaves no remnant after a SN Ia explosion. In contrast, in the SD scenario the companion star survives the explosion and, in principle, can be identified due to its peculiar spatial velocity, its rotation, effective temperature, luminosity or composition \citep{Han2008, WangHua2010a}. Therefore, it is a promising approach to test the progenitors of SNe Ia by directly searching for the surviving companion star in galactic SN remnants (SNRs). There are several ways by which the SN blast wave modifies the properties of the companion. First, the SN strips off matter from the surface of the companion and injects thermal energy into it during the interaction. This causes the surviving companion to expand and lowers its surface gravity. Second, after the impact the companion star’s surface will be enriched with heavy elements (e.g., Ni, Fe or Ca) from the inner part of the SN ejecta which should show up in its spectrum \citep[see][]{GonzalezHernandez2004, Pan2012a}. Finally, after the explosion the companion star retains its pre-explosion orbital velocity, giving it a peculiar velocity compared to other stars in the vicinity.

Tycho Brahe’s SN 1572 is a SN Ia that exploded in the Milky Way \citep{Ruiz-Lapuente2004} have analyzed the stars within a circle of 0.65 arcmin radius of the center of the SNR up to an apparent visual magnitude $V = 22$. They found a star, Tycho G, similar to the Sun in surface temperature and luminosity but with a lower surface gravity than a MS star. It has a significant peculiar velocity in radial and proper motion, and moves at more than three times the mean velocity of the other stars in the field. Therefore, they suggested that Tycho G star could be the surviving companion star of SN 1572. However, since then it has been noted that Tycho G does not show any spectral peculiarities \citep{Hara2007} and that it is apparently not out of thermal equilibrium \citep{Howell2011}. \cite{Fuhrmann2005} also claimed that it might be a thick-disk star coincidently passing in the vicinity of the remnant of SN 1572. Recently, \cite{GonzalezHernandez2009} found that Tycho G has an overabundance of Ni relative to normal metal-rich stars, and they suggest that Tycho G could have captured the low-velocity tail of the SN 1572 ejecta, which upholds Tycho G as a surviving companion star again.

In contrast, in the SD case, because of the strong tidal coupling of a Roche-lobe filling donor, the donor star rotation is expected to be tidally locked to its orbital motion. This forces the binary donor star to have a spin corresponding to the orbital frequency of the binary system \citep{HanPodsiadlowski2003, Kerzendorf2009}. After the SN explosion, the companion is released from its orbit and continues to rotate. Therefore, fast post-explosion rotation might be a signature of the donor star. The survivor could be in rapid rotation which would be measurable easily \cite[see][]{Kerzendorf2009, Kerzendorf2012}. With the HIRES instrument on the Keck-I telescope and with Subaru high-resolution spectroscopy of star G in the Tycho SNR \citep{Kerzendorf2009, Kerzendorf2012} measured the rotational velocity of Tycho G and obtained only $\sim 6 \pm 1.5 \text{ km s}^{-1}$. Thus, they concluded that Tycho G is unlikely to be the surviving companion star of SN 1572 because it does not have the expected high rotational velocity \cite[see][]{Kerzendorf2009, Howell2011}. However, the impact of the SN ejecta strips off material from the surface of the companion star, which can significantly reduce its angular momentum, thereby lowering the rotational velocity. Moreover, the SN impact and heating bloat the companion star, which will also slow down its spin. Recently, \cite{Pan2012a} computed the post-impact evolution of the remnant star produced in their multi-dimensional adaptive mesh refinement simulations of WD+MS-like models with the FLASH code \citep{Pan2012c}. In line with the arguments given above, they conclude that Tycho G cannot be eliminated as being a promising progenitor candidate, based on its low rotational surface velocity only \citep{Pan2012c}.

In this paper, we present the results of 3D SPH simulations of the impact of SN Ia ejecta on a MS companion star including the orbital motion and spin of the companion. The purpose of the work is to investigate how the SN Ia impact changes the rotation rate of the companion which will be useful for identifying the surviving companion star in SNRs. The paper is organized as follows. In Section 2 we describe the codes used and show an example of the initial companion star models used in our simulations. In Section 3 the effect of rotation on the interaction between SN Ia ejecta and its MS companion are discussed. Post-impact rotation features of a MS star are shown in detail in Section 4. Furthermore, the results of our simulations are compared with the observed rotation of star Tycho G in Section 5. Next in Section 6 we discuss the distribution of the rotational velocities of the remnant stars after thermal equilibrium is reestablished. Finally, in Section 7 we summarize our results.

2. Numerical method and model

2.1. Numerical codes and initial setup

In order to obtain consistent MS companion star models at the onset of the SN explosion, similar to \cite{Liu2012}, we used Eggleton’s one-dimensional (1D) stellar evolution code \citep{Eggleton1971, Eggleton1972, Eggleton1973} to follow the binary evolution of a SD progenitor system in detail. Roche-lobe overflow (RLOF) is treated in the code as described by \cite{HanPodsiadlowski2003}. The opacity tables used in our calculations are com-
piled by Chen & Tout (2007), from Iglesias & Rogers (1996) and Alexander & Ferguson (1994). We use a typical Population I composition with hydrogen abundance $X = 0.70$, helium abundance $Y = 0.28$, and metallicity $Z = 0.02$. We set $a = 1/H_p$, the ratio of mixing length to the local pressure scale height, to 2 and set the convective overshooting parameter $\delta$ to 0.12 (Pols et al. 1997; Schröder et al. 1997), which roughly corresponds to an overshooting length of $\sim 0.25$ pressure scale height.

Furthermore, the latest version of the SPH code GADGET-3 (Springel et al. 2001, Springel 2005) is employed to simulate the impact of SN Ia explosions on their MS companions by including the orbital and spin velocities of companion stars. The GADGET code was originally used for cosmological simulations, but it has been modified to make it applicable to stellar astrophysics problems (see [Pakmor et al. 2012a]) and it has been used successfully to capture the main dynamical effects of the SN impact on its companion star (see [Pakmor et al. 2008; Liu et al. 2012]). In our simulations, we aim at determining the rotational velocity of the companion star after the impact. Therefore the fact that no matter leaves the computational domain and that momentum, energy and angular momentum are strictly conserved are a crucial advantage of SPH over grid-based methods for the problem under investigation.

In this work, the basic setup for the GADGET code is almost the same as in Liu et al. (2012). The smoothing length is chosen such that a sphere of its radius encloses 60 neighboring particles. All particles have the same mass. The gravitational softening length is equal to the smoothing length. To reduce numerical noise introduced by mapping the initial model, the MS companion star is relaxed for 1.0 $\times 10^5$ s (several dynamical timescales) before we start the actual impact simulation. The W7 SN Ia model (Nomoto et al. 1984) is used for the SN explosion, and the orbital separation is taken from the 1D consistent binary-evolution calculations.

Additionally, in this work, we assume that the companion star co-rotates with its orbit due to strong tidal interaction. Thus the spin period of the companion star is locked with its orbital period. Furthermore, the orbital and spin velocities of the companion stars are included in our impact simulations in order to study the post-impact rotation rate of surviving star.

The system of coordinates is chosen as follows. We set the $x$–$y$ plane to be the orbital plane of the binary system and assume a circular orbit. The $z$–axis is chosen as the spin axis of the companion, and the positive $z$–axis is the direction of the angular momentum. Finally, we assume that the companion star rotates as a rigid body at the moment of the SN explosion.

### 2.2. Progenitor model

As in Liu et al. (2012) (see also Han & Podsiadlowski 2004, Wang & Han 2010a), we start our 1D consistent binary calculation when the WD+MS system has been formed, the mass transfer then occurs through RLOF when the companion star fills its Roche lobe. Instead of solving the stellar equations for the WD star when we trace the detailed evolution of the companion star, the optically thick wind model of Hachisu et al. (1999) is adopted.

Figure 1 shows the evolution of a binary system with an initial donor-star mass of $M_1 = 2.0 M_\odot$, an initial mass of the CO WD of $M_{\text{WD}} = 0.8 M_\odot$ and an initial orbital period of $\log(P/\text{day}) = 0.2$. In such a system, the companion star has an orbital velocity of 138 km s$^{-1}$ at the moment of the SN Ia explosion. Assuming that the rotation of companion is locked with the orbital motion due to the strong tidal interaction, the rotational velocity, $v_{\text{rot}}$, and its orbital velocity, $v_{\text{orb},2}$, obey a simple relation as follows (see also Kerzendorf et al. 2008):

$$v_{\text{rot}} = \frac{M_1 + M_2}{M_1} f(q) v_{\text{orb},2},$$

where $q = M_2/M_1$ is the mass ratio of the binary system at the moment of the explosion, and $f(q)$ is the ratio of the Roche-lobe radius of companion star to the orbital separation (Fegley 1973). Therefore, we calculate the rotational velocity of the companion star to be $v_{\text{rot}} {\text{SN}} \sim 110$ km s$^{-1}$ at the time of the explosion.

In this model, because hydrogen burning on the WD is unstable before the SN explosion, the system may be observed as a U Sco-type recurrent nova (Hachisu et al. 2008, Mene & Yang 2010). With our consistent binary-evolution calculations, we obtain a CO WD+MS progenitor that is similar to the U Sco binary system with a mass of the secondary of 1.18 $M_\odot$ and an orbital period $\sim 1$ day (see Table 1). This model is named “MS110”, the “MS” indicating a CO WD+MS binary system, the “110” means the rotational velocity of the companion star of $v_{\text{rot}} {\text{SN}} \sim 110$ km s$^{-1}$ at the moment of the explosion. U Scorpii is one of the best-observed recurrent novae, and it has been suggested as a progenitor of a SN Ia because its white dwarf mass is close to the
Chandrasekhar mass (Hachisu et al. 2000; Thoroughgood et al. 2001; Podsiadlowski 2003). In order to investigate the physical parameters of the recurrent nova, Hachisu et al. (2000) have successfully modeled the theoretical light curve for the outburst of the U Scorpii system with a model consisting of a WD mass of $M_{\text{WD}} = 1.37M_\odot$, a secondary mass of $M_2 = 0.8 - 2.0M_\odot$ and an orbital inclination of $\sim 80^\circ$.

3. Effects of rotation

Based on the system similar to U Sco (MS_{110}) that was discussed in Section 2.2, we performed a 3D SPH impact simulation which included the spin velocity of $v_{SN, \text{rot}} = 110\text{ km s}^{-1}$, and the orbital velocity of $v_{SN, \text{orb}} = 138\text{ km s}^{-1}$ to study the effect of asymmetry due to the orbital motion and spin of the companion star. We used a total of $2 \times 10^7$ particles to represent the companion star only (which corresponds to a total number of particles in the simulation of $\sim 4 \times 10^8$). All particles had the same mass of $5.9 \times 10^{-8} M_\odot$. The SN properties were taken from the W7 explosion model (Nomoto et al. 1984) with an initial orbital separation of $3.75 \times 10^{11} \text{ cm}$.

The temporal evolution of the spatial density distribution of, both, the companion and the SN ejecta MS_{110} model with and without including the orbital motion and the rotational velocity of the companion are shown in Fig. 2 and Fig. 3 respectively. Some small morphological differences between the rotating and non-rotating model are seen due to the symmetry-breaking effects of orbital motion and rotation of the companions star (see Fig. 3).

At the end of the simulation, a mass of $\sim 0.23 M_\odot$ ($\sim 19\%$ of the total companion mass) is stripped from the companion star in the MS_{110} model (see Fig. 4). The orbital motion and spin...
of the companion star only leads to a ~ 2% larger unbound mass (see Fig. 4), but basically the same kick velocity (~ 60 km s$^{-1}$). The result differs from what was reported by Pan et al. (2012b), who found that 16% more mass can be stripped if the orbital motion and spin is included. In Section 5 again, we calculate the amount of unbound mass for the model MS$_{160}$ which has a higher rotational velocity of 160 km s$^{-1}$, but still only a 4% difference is found. Moreover, we do not find that the rotation of the companion star significantly affects the post-impact velocity distribution of unbound material and SN Ia ejecta (see Fig. 5). Most of the stripped hydrogen-rich material is confined and hidden close to the center of the SN ejecta. The detection of a hydrogen line may be possible only when the high velocity SN ejecta becomes transparent.

To summarize, the main results (e.g., the unbound mass, the kick velocity) are similar to our previous work (see Pakmor et al. 2008, Liu et al. 2012) even if the orbital and spin velocity of the secondary are taken into account. This is not surprising, since the orbital and spin velocity of the companion star are obviously much lower than the typical values of the expansion velocity of the SN Ia ejecta (~ 10$^{4}$ km s$^{-1}$). Therefore, rotation cannot affect the basic physics of interactions between the SN ejecta and the companion star significantly.

4. Post-impact rotation

In this section, we investigate how the SN Ia explosion affects the rotation of the companion star in our SPH impact simulations by using again the MS$_{110}$ model discussed in detail in Section 2 as a typical case.
4.1. Temporal evolution of the overall rotation

At the time of the SN explosion, the companion star is expected to rotate rapidly at the same frequency as the binary system due to the strong tidal interaction during the RLOF phase. After the SN impact, however, it is uncertain whether it is still possible to use signatures of rapid rotation to single out candidates for donor stars. This depends on the total amount of angular-momentum taken by the stripped material and extreme expansion of the donor star due to SN ejecta heating.

By including the orbital motion and spin of the MS\_110 model, we investigate the total angular momentum that can be carried away by the stripped mass, studying the post-impact evolution of rotational velocity of the surviving companion star. During the interaction, the collision of the SN Ia ejecta brings the companion star out of thermal equilibrium. Simultaneously, the spherical symmetry of the companion star is also strongly affected, deforming the shape of the star (the details of density evolution of a remnant star are shown in Section 4.2). Therefore, it is difficult to determine the real surface of a surviving companion star and to obtain its overall rotational velocity after the SN impact. For this purpose, the two following steps are done to estimate the surface of the surviving companion star in this work:

a) We divide the surviving star into several hundred spherical shells. The density of the SPH particles in each shell are averaged to calculate a value for that shell. Next, if the density fluctuation in a shell is too large, it is ignored because the very outer shells are very poorly resolved anyway (SPH particles in these shells are too rare to reasonably resolve the structure of the star).

b) In Fig. 6, a sharp decrease in density is seen at the outer layer of the surviving companion star. Here, we simply choose the position \( R_2 \) (\( \sim 95\% \) of \( R_1 \)) of the sharp density jump as the real surface of the star (see the vertical dotted line in Fig. 6).

Furthermore, we take the rotation velocity, \( v_{rot} \), at this surface, \( R_2 \), to denote the overall apparent rotational velocity of the surviving companion star. \( v_{rot} \) is set up as a rigid-body rotation, the rotation axis being the initial rotation axis, \( z \)-axis, is \( v_{rot} \).

In the following Section 4.2 it is shown that the rotational velocity is not changing significantly in the outer parts of the stellar envelope. The difference between \( v_{rot} \) and \( v_{rot} \) is \( \lesssim 5\% \).

On the other hand, it is also difficult to determine the exact position of the photosphere of the surviving companion star. However, Figure 6 shows that the density at the position \( R_2 \) starts to decrease sharply. Therefore also the angular velocity and the rotation velocity (see the dashed lines in Fig. 6) decrease significantly. Furthermore, the total angular momentum stops decreasing (see dashed line) as the amount of the stripped mass (solid line) reaches a constant value after 5000 s, which was shown in Fig. 7a. As the companion star is puffed up due to energy deposition from the impact of the SN ejecta, its outer layers expand, remarkably increasing the moment of inertia of the star (see Fig. 7b). This explains why the angular velocity keeps slowly decreasing after 5000 s (see dashed line in Fig. 7), although there is no additional mass-loss and angular-momentum-loss at this moment. However, this expansion does not reduce the rotational velocity of companion significantly as is shown by dashed line in Fig. 7a.

4.2. Post-impact radial-velocity distribution in the companion star

In our simulations, the initial rotation of the companion star was set up as a rigid-body rotation, the rotation axis being the \( z \)-axis. At the moment of the SN explosion, the companion star is spherically symmetric, having the same angular velocity from the center to the surface. Therefore, the rotational velocity increases linearly with radius (see right diagram on the top row of Fig. 8).

Figure 8 shows the density distribution (left column) and the radial profiles of the angular velocity (solid curve), \( \omega_r \), and the rotational velocity (dashed curve), \( v_{rot} \), of the surviving companion star at different times after the explosion for the MS\_110 model. After the SN impact, heating by the SN ejecta puffs up the companion star, causing its envelope to expand considerably. This produces a object with a compact inner core and a low-density outer layer (see left column in Fig. 8). The star starts to relax towards a spherical state about 2\( \times 10^5 \) s after the impact. However, the density in the outer layers varies by as much as a factor of \( \sim 3 \) in different directions (see bottom row in Fig. 8), which was also seen in previous simulations (see Marietta et al. 2000, Pakmor et al. 2008 Liu et al. 2012). At this moment, however, the sound crossing time is still longer than the time we follow in
the simulations (~ 5.6 hours). Therefore, the star does not reach a spherical state.

The right column of Fig. 5 shows that the equatorial rotational velocity of the companion star drops to ~ 25 km s\(^{-1}\) from the original rotational velocity of 110 km s\(^{-1}\) due to the extreme expansion of the star and the angular momentum losses. The angular velocity near the center of the star also decreases below its initial value of 0.8 × 10\(^{-4}\) rad s\(^{-1}\) due to the effect of the shock running through the center, but it becomes stable at late times (see Fig. 9). Additionally, Fig. 8 shows how the radial rotation profiles of the companion star are affected during the collision with the SN Ia ejecta (see also Fig. 9). After the SN impact, the companion star is no longer in rigid-body rotation and its outer layers exhibit some features of differential rotation. At the equator the companion star rotates at a different angular velocity than at higher latitudes. The detailed radial distribution of various rotational properties of model MS\(_{110}\) is shown in Fig. 10. The angular velocity decreases with increasing latitude of the surviving companion star: the equator rotates with a period of ~ 14 days, near the poles it is as small as 2 days. In order ensure that changes of the rotational profile of the companion star are purely caused by the impact of the SN explosion, we have also done a test run without the SN. It shows that without the SN the rotational velocity profile of a companion star does not change at all over the time of the simulation (2 × 10\(^4\) s). In our simulation, we use the rotational velocity at the surface of the post-impact remnant star as the potentially observable velocity. If the photosphere of star should be located at a smaller radius rather than the surface, the rotational velocity would be a little bit higher than ~ 25 km s\(^{-1}\). However, the differences of the rotational velocity are not significant for a large range of outer layers (see Fig. 8 and Fig. 9). Also, in this work, the initial rotation of the companion star is set up in rigid rotation, which might be inconsistent with the realistic rotation of a star. A more realistic rotation profile of the star is required to replace the rigid rotation used here in forthcoming investigations, although we do not expect this to change our main results.

![Fig. 5. Velocity distribution of stripped material that originally belonged to the companion star (left figure) and SN ejecta (right figure) for the non-rotating (solid lines) and rotating (dashed lines) MS\(_{110}\) model.](image)

![Fig. 6. Density profile of the MS\(_{110}\) model for different times after the SN explosion. The black solid line corresponds to the initial density profile of the star at the moment of the explosion. All black dashed lines from @ to @ show the radial density distribution of the star (0.4, 0.8 · · · 2.0) × 10\(^3\) s after the impact in time intervals of 4000 s.](image)

Figure 11 shows the temporal evolution of the radial distribution of the angular momentum of the companion star in model MS\(_{110}\). The different colors belong to different times since the SN explosion. Each colored solid line shows the details of the radial profile of the angular momentum at that given time. The angular momentum, \(J_r\), was calculated by summing up the total angular momentum of all bound particles interior to the corresponding cylindrical surface at radius \(r\). The dashed-dotted line shows the change in total angular momentum as time progresses. Most of the angular momentum of the surviving companion star is concentrated in a small inner core. Outside this core, how-
ever, only a small fraction of the total angular momentum is distributed over an extended outer layer (see Fig. 10).

5. Comparison with Tycho G

Tycho’s SN (SN 1572) is one of only three historical SNe Ia observed in our galaxy. SN 1572 has the advantage that the field of SNR is not so crowded with stars and, therefore, it provides a good opportunity to observationally identify the companion in case of a SD progenitor. Here, we examine the viability of the candidate Tycho G as the possible surviving companion star in SN 1572 by comparing our observed rotational velocity of \( \sim 6 \pm 1.5 \text{ km s}^{-1} \) (Kerzendorf et al. 2009, 2012) with the results of our hydrodynamical simulations.

In our MS-110 model, after the impact, the rotational velocity of the star is significantly reduced to 23% of that before the explosion of \( \sim 110 \text{ km s}^{-1} \) (see Table 1). In Section 4.1 we discussed that the surface spin of the companion star is roughly constant from 5000 s after the explosion. However, we stopped our simulation \( 2 \times 10^3 \) s after the explosion because of the high computational costs. Podsialedowski (2003) followed the post-impact evolution of the surviving companion star further and showed that the star might reestablish thermal equilibrium \( \sim 10^3 \) yr after the explosion (see also Pan et al. 2012a). Figure 9 shows that the radial distribution of the rotational velocity of the surviving companion becomes approximately constant \( \sim 1 \times 10^3 \) s after the SN explosion, and the surface velocity at the equator is converged at the end of our hydrodynamics simulations. Therefore, we can safely assume that the surface velocity at the equator of the post-impact companion star would keep a stable value until its thermal equilibrium is established after a few thousand years. Considering that the Tycho SN remnant is only 439 years old, the spin of the MS-110 model (\( \sim 25 \text{ km s}^{-1} \)) after the impact is far larger than the observational rotational velocity of the star Tycho G (\( 6 \pm 1.5 \text{ km s}^{-1} \) according to Kerzendorf et al. 2009, 2012).

Han (2008) carried out detailed binary evolution calculations for the WD+MS channel of SNe Ia, in which RLOF starts when the companion star is on the MS or in the Hertzsprung-gap phase. They obtained many properties of the companion star at the moment of the SN explosion (e.g. their masses, spatial velocity, effective temperature, luminosity, surface gravity, etc). These properties might be verified by the observations. The distribution of properties of companion stars in the plane of (\( v_{\text{rot}}^\text{SN} \), \( M_{\text{bd}}^\text{SN} \)) from Han (2008) is shown in Fig. 12. Based on the observations of Kerzendorf et al. (2009, 2012), the location of the rotation of the star Tycho G is shown with black error bars. Clearly, because of the bound rotation before the impact, Tycho G is far away from the allowed region.

Next we estimate the rotational velocity of the stars shown in Fig. 12, after the impact. In order to obtain the distribution of rotational velocities of surviving companions after the SN Ia explosion, we re-perform 1D consistent binary evolution calculations to construct the structures of the companions, obtaining additional three consistent models named “MS_2011”, “MS_131”
Table 1. SPH impact simulations for four different MS companion models.

| Model name | $M_{2}^{SN}$ [M$_\odot$] | $P_{SN}$ [days] | $R_{2}^{SN}$ [R$_\odot$] | $a_{SN}$ [km/s] | $v_{rot}^SN$ [km/s] | $M_{bound}$ [M$_\odot$] |
|------------|--------------------------|-----------------|------------------------|----------------|-------------------|-----------------------|
| MS_160     | 1.21                     | 0.29            | 0.93                   | 2.55           | 160               | 52                    | 98 | 2.94 | 1.31 | 1.04 |
| MS_131     | 1.23                     | 0.56            | 1.45                   | 3.94           | 131               | 40                    | 78 | 2.07 | 0.92 | 1.06 |
| MS_110     | 1.18                     | 0.91            | 1.97                   | 5.39           | 110               | 25                    | 46 | 2.25 | 0.62 | 0.95 |
| MS_081     | 1.09                     | 2.00            | 3.19                   | 8.92           | 81                | 12                    | 16 | 2.32 | 0.26 | 0.84 |

Here, $M_{2}^{SN}$, $P_{SN}$, $R_{2}^{SN}$, $a_{SN}$, $v_{rot}^SN$ and $J_{spin}^{SN}$ are the mass, the orbital period, the radius, the spin velocity and angular momentum of the companion star at the moment of the explosion, respectively. $v_{rot}^f$, $J_{spin}^f$ and $M_{bound}$ denote the spin velocity, the angular momentum, and the total bound mass of the companion star after the SN impact. $v_{rot}^f$ is the rotational velocity at the surface after the thermal equilibrium is reestablished. Note that the rotational velocity, $v_{rot}^SN$, is calculated by assuming that the rotation of the star is locked with the orbital motion due to tidal interactions.

Fig. 8. Left column: temporal evolution of the density distribution of the surviving companion star in model MS_110. Right column: temporal evolution of the radial configurations of the angular velocity, $\omega$ (solid line), and the rotational velocity, $v_{rot}$ (dashed line). $R$ is the distance from the rotation axes, the $z$-axis. Please note that we use different length scales in different diagrams.
and “MS$_{160}$” with different rotational velocities of 81 km s$^{-1}$, 131 km s$^{-1}$ and 160 km s$^{-1}$ (see Table 1). We then use these three models as input into our impact simulations to investigate the dependence of the rotational velocity of companion star after the impact on its value before the explosion. The properties of all companion models are shown in Table 1. We find that to a good approximation the post-impact rotational velocity of star scales linearly with the pre-explosion velocity as is shown in Fig. 13 and can be fitted by

$$V_{rot}^{f} = 0.52 \cdot V_{rot}^{\text{SN}} - 29.8 \text{ (km s}^{-1}),$$

where $V_{rot}^{f}$ is the post-impact rotational velocity at the end of the simulations, and $V_{rot}^{\text{SN}}$ corresponds to the star’s initial rotational velocity at the moment of the explosion.

In the previous work of Liu et al. (2012), it was found that the unbound mass of the companion star caused by the SN impact is strongly dependent on the ratio of separation to the radius of the companion star, $a_{1}/R_{2}$. This relation can be fitted by a power law if the effect of the different structures of the companion stars is neglected (see also Marietta et al. 2000; Pakmor et al. 2008; Pan et al. 2012).

$$M_{sp} = C_{1} \cdot \left( \frac{a_{1}}{R_{2}} \right)^{\beta} M_{\odot},$$

where $C_{1}$ is a fitting constant which depends on the different companion star models. The parameter $\beta$ is the corresponding power-law index.

Therefore, adopting above power-law relation (see also equation (2) of Liu et al. 2012) and the linear relation (2) obtained from the data shown in Fig. 13, we calculate the final bound mass and the post-impact rotational velocity of surviving companion stars on all companion models from the population synthesis study of Han (2008). The results are presented in Fig. 12. The location of Tycho G is also shown with a black error bars. Here, we assume that Tycho G is a one solar mass star (Ruiz-Lapuente et al. 2004) and its rotational velocity is $6 \pm 1.5$ km s$^{-1}$ (Kerzendorf et al. 2012). Fig. 12 shows that Tycho G is located in the outer region of 95.4% of all systems, which casts doubt on Tycho G star as a promising candidate in SD progenitors of SNe Ia.

However, it is not possible to exclude the star Tycho G completely for several reasons.

1. The errors shown in Fig. 12 are based on an assumption that Tycho G is a one solar mass star (Ruiz-Lapuente et al. 2004). However, it is very difficult to determine the actual mass from the observations. Therefore, Tycho G should be located in the vertical gray strip at its given rotation velocity in Fig. 12. If Tycho G is a 0.6 – 0.7 $M_{\odot}$ star rather a solar mass star, it could more likely be a candidate for the companion star of SN 1572 in the SD scenario. Moreover, the errors given in Fig. 12 are based on an assumption that the observed rotational velocity of Tycho G is reduced by an inclination angle of 60$^\circ$. However, if the inclination angle is 30$^\circ$ instead...
assumed inclination angle of 5% error (Ruiz-Lapuente et al. 2004) and an inclination angle of Tycho G according to Kerzendorf et al. (2009, 2012) employing the linear relation shown in Fig. 13 (see text). The impact rotational velocity of companion star is computed evaluated by using equation (2) of Liu et al. (2012), and the post-impact masses of the companion stars shown in Fig. 12 are calculated by directly adopting the power law relation from equation (2) of Liu et al. (2012), which ignores the effect of the different companion structures. However, Liu et al. (2012) found that the details of the companion structure also plays an important role in determining the amount of unbound mass caused by the impact. Nonetheless, the ratio of separation to the radius of companion star, $a/R_\star$, is the most important parameter to determine the unbound mass (Liu et al. 2012).

3. The post-impact masses of the companion stars shown in Fig. 12 are calculated by directly adopting the power law relation from equation (2) of Liu et al. (2012), which ignores the effect of the different companion structures. However, Liu et al. (2012) found that the details of the companion structure also plays an important role in determining the amount of unbound mass caused by the impact. Nonetheless, the ratio of separation to the radius of companion star, $a/R_\star$, is the most important parameter to determine the unbound mass (Liu et al. 2012).

4. We assume that the surviving companion star has a constant surface rotational velocity after ~5000 s after the SN Ia impact. However, we only carried out our simulations to $2 \times 10^4$ s after the explosion. Extended calculations based on the results of our impact simulations are still required to follow in detail the post-impact rotation of the star during its re-equilibration phase. For instance, very recently Pan et al. (2012b) showed that the remnant star after the SN impact could continue to expand on a local thermal timescale of $\sim10^3$ yrs before it shrinks again.

6. Rotation velocity after re-equilibration

After the supernova impact, the companion star puffs up and the stellar envelope is out of thermal equilibrium. The post-impact remnant star will recover the state of thermal equilibrium on the Kelvin-Helmholtz timescale of $\sim10^3$–$10^5$ yrs (Pan et al. 2012a; Marietta et al. 2000; Podsiadlowski 2003). In order to estimate the rotation rate after thermal equilibrium is reestablished, we...
make the simplifying assumption that the remnant star has constant rotational velocity during the re-equilibration phase. After thermal equilibrium is established, the post-impact remnant star will shrink and return to the state of a MS-like star. As a result, the surface rotational velocity of the remnant star will increase again, and we assume that the angular momentum of the star would redistribute towards rigid-body rotation. If the angular momentum is given roughly by $J = aMR^2\omega$ before the SN explosion and after re-equilibration, and also has a constant value of the parameter $a$, the rotational velocity ($v_{\text{rot}}^f$) of the remnant star after the re-equilibration can be determined once the radius of the re-equilibrium star, $R$, is fixed. In order to estimate the final radius of the remnant star, the MS relation $R \propto M^{2/3}$ is used (see also Marietta et al. 2000). By adopting the post-impact angular momentum, $J_{\text{spin}}^f$, and the value of $a$ that is calculated for the pre-SN companion star model, we can estimate the rotational velocity of the remnant star after the thermal equilibrium is reestablished. The rotational velocity of different companion-star models before the explosion and after the re-equilibration can also be fitted with a linear relation in good approximation (see Fig. 15a). In Fig. 15b we also show the distribution of the rotational velocities, $v_{\text{rot}}^f$ after re-equilibration, employing the same method as in Section 5. It can be seen that the companion stars relax to higher rotation velocity again after the thermal equilibrium is reestablished (at least about a few thousand years after the SN explosion).

7. Summary and conclusions

In this work, we have modeled the impact of SN Ia ejecta on their MS companion stars by means of 3D SPH hydrodynamical simulations which included the orbital and spin velocity of the companion stars. The MS companion stars were constructed by using Eggleton’s 1D stellar evolution code making use of the optically thick wind model of Hachisu et al. (1999). We found that the orbital motion and the spin of the companion star do not significantly affect the amount of unbound mass and the kick velocity caused by the SN impact. This result, obtained with a SPH code, differs from what was found previously by Pan et al. (2012b), who from their grid-based FLASH code simulations concluded that these two properties increase the amount of unbound mass by up to ~ 16%, but also found that the kick velocity is not affected. We have shown that the SN impact affects the rotation rate of the companion stars and their rotation laws. In our simulations we found that the SN impact removes as much as 55% to 89% of the initial angular momentum due to the fact that 14% to 23% of the initial mass is stripped from the MS companion star. The remnant expands significantly after the impact which causes the equatorial surface rotational velocity to drop significantly to 14% to 32% of the original value. Additionally, we found that the post-impact rotational velocities of companion stars depend linearly on those prior to the explosion. Compared with the observed rotational velocity of the presumed companion star of Tycho’s supernova, Tycho G, the final rotational velocity we obtain in our simulations is still higher by at least a factor of two. Whether or no this difference is significant, and may cast doubts on the suggestion that Tycho G is the companion of SN 1572, has to be investigated in future studies. In particular, having a more accurate mass and inclination of Tycho G would help, as well as simulations that follow the evolution for much longer than we can do with our explicit SPH code. Furthermore, by using the population synthesis results of Hart (2008), we showed...
the distributions of the rotational velocities of surviving companions after the impact, which may be very useful for further observations to identify the surviving companion stars in SNRs.

Acknowledgments

Z.W.L and Z.W.H thank the financial support from the MPG-CAS Joint Doctoral Promotion Program (DP) and Max Planck Institute for Astrophysics (MPA). This work is supported by the National Basic Research Program of China (Grant No. 2009CB824800), the National Natural Science Foundation of China (Grant Nos. 11033008 and 11103072) and the Chinese Academy of Sciences (Grant No. JCS2-WY-T24). The work of F.K.R was supported by Deutsche Forschungsgemeinschaft via the Emmy Noether Program (RO 3676/1-1) and by the ARCHES prize of the German Federal Ministry of Education and Research (BMBF). The simulations were carried out at the Computing Center of the Max Planck Society, Garching, Germany.

References

Alexander, D. R. & Ferguson, J. W. 1994, ApJ, 437, 879
Chen, X.-F. & Tout, C. A. 2007, Chinese J. Astron. Astrophys., 7, 245
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Science, 337, 942
Eggleton, P. P. 1971, MNRAS, 151, 351
Eggleton, P. P. 1972, MNRAS, 156, 361
Eggleton, P. P. 1973, MNRAS, 163, 279
Foley, R. J., Kromer, M., Howie Marion, G., et al. 2012, ApJ, 753, L5
Fuhrmann, K. 2005, MNRAS, 359, L35
González Hernández, J. I., Ruiz-Lapuente, P., Filippenko, A. V., et al. 2009, ApJ, 691, 1
Hachisu, I., Kato, M., Kato, T., & Matsumoto, K. 2000, ApJ, 528, L97
Hachisu, I., Kato, M., & Nomoto, K. 2008, ApJL, 679, 1390.
Hachisu, I., Kato, M., Nomoto, K., & Umeda, H. 1999, ApJ, 519, 314
Han, Z. 2008, ApJ, 677, L109
Han, Z. & Podsiadlowski, P. 2004, MNRAS, 350, 1301
Hillebrandt, W. & Niemeyer, J. C. 2000, ARA&A, 38, 191
Howell, D. A. 2011, Nature Communications, 2
Hoyle, F. & Fowler, W. A. 1960, ApJ, 132, 565
Iben, Jr., I. & Tutukov, A. V. 1984, ApJS, 54, 335
Iglesias, C. A. & Rogers, F. J. 1996, ApJ, 464, 943
Ihara, Y., Ozaki, J., Doi, M., et al. 2007, PASJ, 59, 811
Kerzendorf, W. E., Schmidt, B. P., Asplund, M., et al. 2009, ApJ, 701, 1665
Kerzendorf, W. E., Yong, D., Schmidt, B. P., et al. 2012, arXiv:1210.2713
Leibundgut, B. 2008, General Relativity and Gravitation, 40, 221
Leonard, D. C. 2007, ApJ, 670, 1275
Liu, Z. W., Pakmor, R., Röpke, F. K., et al. 2012, A&A, 548, A2
Marietta, E., Burrows, A., & Fryxell, B. 2000, ApJS, 128, 615
Meng, X. & Yang, W. 2010, ApJ, 710, 1310
Nomoto, K., Iwamoto, K., & Kishimoto, N. 1997, Science, 276, 1378
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644
Pakmor, R., Edelmann, P., Röpke, F. K., & Hillebrandt, W. 2012a, MNRAS, 424, 2222
Pakmor, R., Hachinger, S., Röpke, F. K., & Hillebrandt, W. 2011, A&A, 528, A117
Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, Nature, 463, 61
Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012b, ApJ, 747, L10
Pakmor, R., Röpke, F. K., Weiss, A., & Hillebrandt, W. 2008, A&A, 489, 943
Pan, K.-C., Ricker, P. M., & Taam, R. E. 2010, ApJ, 715, 78
Pan, K.-C., Ricker, P. M., & Taam, R. E. 2012a, ApJ, 760, 21
Pan, K.-C., Ricker, P. M., & Taam, R. E. 2012b, ApJ, 750, 151
Patat, F., Chandra, P., Chevalier, R., et al. 2007, Science, 317, 924
Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M., Lira, P., Suntzeff, N. B., et al. 1999, AJ, 118, 1766
Podsiadlowski, P. 2003, arXiv:astro-ph/0303660
Pols, O. R., Tout, C. A., Schroder, K.-P., Eggleton, P. P., & Manners, J. 1997, MNRAS, 289, 869
Price, D. J. 2007, PASA, 24, 159
Ricker, P. M., Pan, K.-C., & Taam, R. E. 2010, in American Institute of Physics Conference Series, Vol. 1314, American Institute of Physics Conference Series, ed. V. Kologer & M. van der Sluys, 250–255
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
Ruiz-Lapuente, P., Comeron, F., Méndez, J., et al. 2004, Nature, 431, 1069
Schroder, K.-P., Pols, O. R., & Eggleton, P. P. 1997, MNRAS, 285, 696
Shappee, B. J., Stanek, K. Z., Pogge, R. W., & Garnavich, P. M. 2013, ApJ, 762, L5
Springel, V. 2005, MNRAS, 364, 1105
Springel, V., Yoshida, N., & White, S. D. M. 2001, New A, 6, 79
Sternberg, A., Gal-Yam, A., Simon, J. D., et al. 2011, Science, 333, 856
Thoroughgood, T. D., Dhillon, V. S., Littlefair, S. P., Marsh, T. R., & Smith, D. A. 2001, MNRAS, 327, 1323
Wang, B. & Han, Z. 2010a, MNRAS, 404, L84
Wang, B. & Han, Z. 2010b, A&A, 515, A88
Wang, B. & Han, Z. 2012, New A Rev., 56, 122
Weinberg, R. F. 1984, ApJ, 277, 355