WD + MS systems as the progenitor of SNe Ia

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Abstract The single-degenerate (SD) channel for the progenitors of type Ia supernovae (SNe Ia) is one of the most popular channels, in which a carbon-oxygen white dwarf (CO WD) accretes hydrogen-rich material from its companion, increases its mass to the Chandrasekhar mass limit, and then explodes as a SN Ia. We show the initial and final parameter space for SNe Ia in a (log $P$, $M_2$) plane and find that the positions of some famous recurrent novae, as well as a supersoft X-ray source (SSS), RX J0513.9-6951, are well explained by our model. The model can also explain the space velocity and mass of Tycho G, which is now suggested to be the companion star of Tycho’s supernova. Our study indicates that the SSS, V Sge, might be the potential progenitor of supernovae like SN 2002ic if the delayed dynamical-instability model due to Han & Podsiadlowski (2006) is appropriate. Among all the progenitor models, the single-degenerate (SD) Chandrasekhar model is widely studied (Yungelson et al. 1995; Li & van den Heuvel 1997; Hachisu et al. 1999a, 1999b; Nomoto et al. 1999; Langer et al. 2000; Han & Podsiadlowski 2004; Chen & Li 2007; Han 2008; Meng, Chen & Han 2009; Liu et al. 2009) and upheld by many observation, e.g. the discovery of the potential companion of Tycho’s supernova (Ríos-Lapuente et al. 2004) and the variable circumstellar absorption lines (Patat et al. 2007). In the SD model, the maximum stable mass of the CO WD is $\sim 1.378 M_\odot$ (close to the Chandrasekhar mass, Nomoto, Thielemann & Yokoi 1984), and the companion is probably a main sequence star or a slightly evolved star (WD+MS), or a red-giant star (WD+RG) (Whelan & Iben 1973; Nomoto, Thielemann & Yokoi 1984). In the paper, we focus on the WD+MS channel, which is a very important channel to contribute to SNe Ia.

Keywords stars: binaries: general—stars: supernovae: general—individual(SN 2002ic, SN 2006X)—stars: white dwarfs

1 Introduction

Type Ia supernovae (SNe Ia) play an important role as cosmological distance indicators to measure cosmological parameters (e.g. $\Omega$ and $\Lambda$; Riess et al. 1998; Perlmutter et al. 1999), which have led to the discovery of the accelerating expansion of the universe. However, the exact nature of SNe Ia progenitors has not been clear (see the reviews by Hillebrandt & Niemeyer 2000; Leibundgut 2000). It is widely accepted that a SN Ia originates from the thermonuclear runaway of a carbon-oxygen white dwarf (CO WD) in a binary system. The CO WD accretes material from its companion, increases mass to its maximum stable mass, and then explodes as a thermonuclear runaway (Branch 2004). Among all the progenitor models, the single-degenerate (SD) Chandrasekhar model is widely studied (Yungelson et al. 1995; Li & van den Heuvel 1997; Hachisu et al. 1999a, 1999b; Nomoto et al. 1999; Langer et al. 2000; Han & Podsiadlowski 2004; Chen & Li 2007; Han 2008; Meng, Chen & Han 2009; Liu et al. 2009) and upheld by many observation, e.g. the discovery of the potential companion of Tycho’s supernova (Ruiz-Lapuente et al. 2004) and the variable circumstellar absorption lines (Patat et al. 2007). In the SD model, the maximum stable mass of the CO WD is $\sim 1.378 M_\odot$ (close to the Chandrasekhar mass, Nomoto, Thielemann & Yokoi 1984), and the companion is probably a main sequence star or a slightly evolved star (WD+MS), or a red-giant star (WD+RG) (Whelan & Iben 1973; Nomoto, Thielemann & Yokoi 1984). In the paper, we focus on the WD+MS channel, which is a very important channel to contribute to SNe Ia.

The paper is organized as follows: we describe our methods in Section 2, show our results in Section 3, present some discussions in Section 4, and then finally in Section 5, we give our conclusions.

2 Methods

Our method for treating the binary evolution of WD + MS systems is the same as that in Meng, Chen &
Han (2009), and here, we only give a simple description. We use the stellar evolution code of Eggleton (1971, 1972, 1973) to calculate the binary evolutions of WD+MS systems. Instead of solving the stellar structure equations of a WD, we adopt the prescription of Hachisu et al. (1999a) on WDS accreting hydrogen-rich material from their companions. We assume that if the mass-transfer rate, $|\dot{M}_2|$, between WD and its companion is larger than a critical value, $M_{\text{cr}}$, the accreted hydrogen-rich material steadily burns on the surface of WD at the rate of $\dot{M}_{\text{wind}} = |\dot{M}_2| - M_{\text{cr}}$ (Hachisu et al. 1996). The material lost as the optically thick wind may exist as circumstellar material (CSM) and be a possible origin of color excess of SNe Ia (Meng et al. 2009).

When $|\dot{M}_2|$ locates in the range of $M_{\text{cr}}$ to $\frac{1}{2} M_{\text{cr}}$, the hydrogen burning is stable or weakly unstable and no material is lost from the system. If $|\dot{M}_2|$ is smaller than $\frac{1}{2} M_{\text{cr}}$, the hydrogen burning is heavily unstable and no material accumulates on the surface of the WD. The hydrogen-rich material accumulated is converted into helium. When the mass of the helium reaches a certain value, a helium flash may occur and a part of helium may be lost from the system. The mass accumulation efficiency for helium-shell flashes is from Kato & Hachisu (2004). If the mass of a WD can reach $1.378 M_\odot$, we assume that the WD explodes as a SN Ia.

### 3 Results

#### 3.1 initial and final parameters space

We carried out a detailed binary evolution calculation for more than 25,000 WD+MS systems with various metallicities, and we obtained a large, dense model grid. The final outcomes of all the binary evolution calculations are summarized in the initial orbital period-secondary mass ($\log P - M_2^i$) plane (see Figs. 2 and 3 in Meng, Chen & Han 2009).

Our results may provide help to judge whether a WD + MS system may explode as a SN Ia. In Fig. 1, we show the initial contour for SNe Ia and the final state of binary evolution in the ($\log P - M_2$) plane at the moment of SNe Ia explosion. The final state of the WD + MS system in the plane is encircled by a dot-dashed line (labeled “initial”). Filled squares indicate SN Ia explosions during an optically thick wind phase. Filled circles and filled triangles denote SN Ia explosions after the wind phase while hydrogen-shell burning is stable or mildly unstable, respectively. A supersoft X-ray source, RX J0513.9-6951, (open star) is plotted. Three recurrent novae are indicated by a filled star, a solar symbol and an earth symbol, respectively.

#### 3.2 companion properties

We also show the parameter spaces for companions at the moment of supernova explosion. In Fig. 2, we show the final states of the companions with various metallicities at the moment of supernova explosion in the ($M_2^{\text{SN}} - V_{\text{orb}}$) (final companion mass - orbital velocity) plane. We noticed that the suggested companion star of Tycho’s supernova, Tycho G, locates in the permitted region and all metallicities seem to account for the position of the potential companion. Actually, the detailed binary population synthesis results show that only the case of $Z = 0.02$ is appropriate for Tycho G (see also Meng, Yang & Geng 2009).
3.3 SN 2002ic

SN 2002ic is the first object showing hydrogen lines in its spectrum, which is interpreted as the interaction between supernova ejecta and CSM (Hamuy et al. 2003). Many models have been suggested to explain this rare object. Among all the models, the delayed dynamical-instability model suggested by Han & Podsiadlowski (2006) is more interesting and some predictions from the model seem to be consistent with observations, especially in the sense of the birth rate and delay time of the rare object (Aldering et al. 2006; Prieto et al. 2007). In the scenario of Han & Podsiadlowski (2006), SN 2002ic may be from the WD + MS channel, where the CO WD accretes material from its relatively massive companion (∼ 3.0$M_\odot$), and increases its mass to 1.30 $M_\odot$ before experiencing a delayed dynamical instability. Following the study of Han & Podsiadlowski (2006), Meng, Chen & Han (2009) showed the parameter space for SN 2002ic with various metallicities and predicated that supernovae like SN 2002ic may not be found in extremely low-metallicity environments. However, more evidence is necessary to confirm the scenario suggested by Han & Podsiadlowski (2006), especially to find a progenitor system.

V Sge is a well observed quasi-periodic transient SSS in our Galaxy. We found that it just locates at the boundary of parameters for SN 2002ic in (log $P$, $M_2$) plane. The mass-loss rate for V Sge can be as large as $\sim 10^{-5}$ $M_\odot$ yr$^{-1}$, indicated by radio observation (Lockley et al. 1997, 1999), which is consistent with the prediction from the delayed dynamical-instability model. So, it is possible that V Sge is the first candidate of the progenitor of supernovae like SN 2002ic if the delayed dynamical-instability model in Han & Podsiadlowski (2006) is appropriate. Based on the prediction from Han & Podsiadlowski (2006) that 1 in 100 SNe Ia belongs to the subgroup of 2002ic-like supernovae and considering that the life time of V Sge is $\sim 10^5$ yr, there should be several V Sge-type stars belonging to the WD + MS system in our Galaxy if we take the Galactic birth rate of SNe Ia as $3-4 \times 10^{-3}$ yr$^{-1}$ (van den Bergh & Tammann 1991; Cappellaro & Turatto 1997). Observationally, Steiner & Diaz (1998) listed four V Sge-type stars in the Galaxy and discussed their similar spectroscopic and photometric properties. So, the number of V Sge-type stars is also consistent with the prediction from the delayed dynamical-instability model.

3.4 the birth rate

Incorporating our results into Hurleys rapid stellar evolution code (Hurley et al. 2000, 2002), we calculate the birth rate of SNe Ia for the WD+MS model. We use Monte Carlo simulation to generate a primordial binary sample (see Meng, Chen & Han 2009 for the basic parameters for Monte Carlo simulation). We found that for the case of single star burst, most supernovae occur between 0.1 Gyr and 2 Gyr after star formation, and a high metallicity leads to a systematically earlier explosion time. The peak value of the birth rate increases with metallicity Z. However, the WD+MS model only can account for about 30 percent of the Galactic birth rate (see also Meng, Chen & Han 2009).

3.5 SN 2006X

SN 2006X is the first case to show the signal of circumstellar material, which shows its single-degenerate nature (Patat et al. 2007). Patat et al. (2007) suggested that the progenitor of SN 2006X is a WD + RG system based on the expansion velocity of the circumstellar material. Blondin et al. (2009) found that 6 in
100 SNe Ia should belong to the rare group. Hachisu et al. (2008) suggested that SN 2006X may be from a WD + MS system, and if a WD explodes at the optically thick wind phase, the SN may show a signal like SN 2006X. Following the study of Meng, Chen & Han (2009), we calculated the evolution of the birth rate of supernovae like SN 2006X by assuming that if a SN Ia explodes at the optically thick wind phase, it is a 2006X-like supernova. We found that the progenitor age of SN 2006X is between 0.3 Gyr and 1 Gyr, which means that there is star formation during the recent 1 Gyr in the host galaxy of supernovae like SN 2006X. The host galaxies of SN 2006X and its twins, SN 1999cl, are both spiral galaxies, and show a significant signal of star formation at present (Kanpen et al. 1993, 1996; Wong & Blitz 2002). We also noticed that supernovae like SN 2006X are a relatively rare subclass of SNe Ia: 1 in 100 SNe Ia can be of this type, which depends on the common envelope ejection efficiency, $\alpha_{CE}$. The birth rate found by Blondin et al. (2009) if located in the range. So, our results uphold the suggestion of Hachisu et al. (2008) that the progenitor system of a supernova like SN 2006X may be a WD + MS system (see Meng, Yang & Geng 2009b).

3.6 color excess

In our binary evolution calculation, we assume that a part of the hydrogen-rich material may be lost from the binary system as an optically thick wind. The lost material may exist as circumstellar material (CSM). If this scenario is appropriate, the CSM should be the origin of the color excess of SNe Ia. Reindl et al. (2005) showed the color excesses to be more than one hundred SNe Ia at maximum light, which provides an opportunity to check whether the SD model may reproduce the distribution of the color excess of SNe Ia. Following the study of Meng, Chen & Han (2009) and via a simple analytic method, we may reproduce the distribution of color excesses of SNe Ia by our binary population synthesis (BPS) approach if the velocity of the optically thick wind is taken to be of the order of 10 km s$^{-1}$. However, if the wind velocity is larger than 10 km s$^{-1}$, the reproduction is bad (see Meng et al. 2009 for details).

3.7 Tycho G

Following the study of Meng, Chen & Han (2009) and via a BPS approach, we calculated the distributions of the parameters of the binary systems at the moment of supernova explosion and the properties of companions after supernova explosion, e.g. mass, radius, space velocity and surface gravity. The former may provide physics input when one simulates the interaction between supernova ejecta and its companion, and the latter may help to search for the companions in supernova remnants. It is surprising that the properties of the potential companion of Tycho’s supernova, Tycho G, are well consistent with our BPS results, and only the case of $Z = 0.02$ may account for the properties of Tycho G (please, see our following paper: Meng & Yang 2009). However, a conclusive result about Tycho G is premature, since there have been considerable debates about whether the star is related to Tycho’s supernova (Kerzendorf et al. 2009; Hernández et al. 2009).

3.8 polarization

After the explosion, the explosion ejecta impacts into the envelope of the companion and strips off some hydrogen-rich material from the surface of the companion. Because of the existence of the companion, a hole forms in the explosion ejecta and the hole will never disappear since the movement of the ejecta is supersonic. Then the explosion remnant is aspheric, and the aspheric structure may reveal itself by a polarized spectrum (Marietta et al. 2000; Meng, Chen & Han 2007). Based on the numerical simulation of Marietta et al. (2000) and Kasen et al. (2004), we found that at least 75% of all SNe Ia can be detected by observation of the polarization. At present, all supernovae which are observed by spectropolarimetry have various degrees of polarization signal (Leonard et al. 2005).

4 Discussion

From our study, the WD + MS channel can only account for about 1/3 of the SNe Ia observed. Therefore, there may be other channels or mechanisms contributing to SNe Ia. A wide symbiotic system, WD + RG, is a possible progenitor of SNe Ia. Now, we are constructing a complete model including WD + MS channel and WD + RG channel, hoping to resolve the problem. In our new model, the range of the companion mass for SNe Ia is from 0.6 $M_\odot$ to 5 $M_\odot$. The mass of WD contributing to SNe Ia may be as low as 0.565 $M_\odot$.

An alternative is the double-degenerate (DD) channel. Although, it is theoretically less favored, observation showed that it may contribute to a few SNe Ia, e.g. SN 2003fg and SN 2006gz (Howell et al. 2006; Hicken et al. 2007). So, at present it is premature to obtain a definitive conclusion for the DD model.
5 Conclusion

The WD+MS channel is a very important channel for SNe Ia and the channel may contribute to SNe Ia by about 30%. Based on a detailed binary evolution calculation, we show the initial and final parameter space for SNe Ia in the ($\log P^i, M^i_2$) plane. The results may provide help to survey potential candidates of SNe Ia. Following the results of Meng, Chen & Han (2009) and via a binary population synthesis approach, we found that the SD channel may reproduce the birth rate of SN 2006X and the distribution of color excess of SNe Ia. The properties of the potential companion of Tycho’s supernova, Tycho G, may also be consistent with our BPS results.
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