Birthrates and delay times of Type Ia supernovae

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ABSTRACT

Type Ia supernovae (SNe Ia) play an important role in diverse areas of astrophysics, from the chemical evolution of galaxies to observational cosmology. However, the nature of the progenitors of SNe Ia is still unclear. In this paper, according to a detailed binary population synthesis study, we obtained SN Ia birthrates and delay times from different progenitor models, and compared them with observations. We find that the Galactic SN Ia birthrate from the double-degenerate (DD) model is close to those inferred from observations, while the birthrate from the single-degenerate (SD) model accounts for only about $1/2-2/3$ of the observations. If a single starburst is assumed, the distribution of the delay times of SNe Ia from the SD model is a weak bimodality, where the WD + He channel contributes to the SNe Ia with delay times shorter than 100 Myr, and the WD + MS and WD + RG channels to those with age longer than 1 Gyr.

Subject headings: binaries: close — stars: evolution — supernovae: general — white dwarfs

1. Introduction

Type Ia supernovae (SNe Ia) appear to be good cosmological distance indicators due to their high luminosities and remarkable uniformity, and thus are used for determining cosmological parameters(e.g., Riess et al. 1998; Perlmutter et al. 1999). They also throw light on the understanding of galactic chemical evolution owing to the main contribution of iron to their host galaxies. However, several key issues related to the nature of their progenitor systems and the physics of the explosion mechanisms are still not well understood(Hillebrandt

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& Niemeyer 2000; Wang et al. 2008a), and no SN Ia progenitor system before the explosion has been conclusively identified. This may raise doubts about the distance calibration, which is purely empirical and based on the SN Ia sample of the low red-shift universe.

It is generally believed that SNe Ia are thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) in binaries. Over the past few decades, two families of SN Ia progenitor models have been proposed, i.e., the double-degenerate (DD) and single-degenerate (SD) models. The DD model involves the merger of two CO WDs, where the total mass of the two CO WDs is larger than the Chandrasekhar (Ch) mass limit (Webbink 1984; Han 1998). For the SD model, the companion is probably a main-sequence (MS) star or a slightly evolved subgiant star (WD + MS channel), or a red giant star (WD + RG channel), or an He star (WD + He star channel) (Hachisu et al. 1999; Li & van den Heuvel 1997; Han & Podsialdowski 2004; Chen & Li 2009; Meng et al. 2009; Lü et al. 2009; Wang et al. 2009a; Wang, Li & Han 2010). Note that, recent observations have suggested that at least some SNe Ia can be produced by a variety of progenitor systems (e.g., Patat et al. 2007; Wang et al. 2008b).

At present, various progenitor models of SNe Ia can be examined by comparing the distribution of the delay time (between the star formation and SN Ia explosion) expected from a progenitor model with that of observations (e.g., Chen & Li 2007; Wang & Han 2010). There are three important observational results for SNe Ia, i.e., the strong enhancement of the SN Ia birthrate in radio-loud early-type galaxies, the strong dependence of the SN Ia birthrate on the colors of the host galaxies, and the evolution of the SN Ia birthrate with redshift. Mannucci et al. (2006) found that the observational results can be best matched by a bimodal delay time distribution, in which about half of the SNe Ia explode soon after starburst, with a delay time less than $\sim$100 Myr, while those remaining have a much wider distribution with a delay time of $\sim$3 Gyr. It is suggested that 10% (weak bimodality) to 50% (strong bimodality) of all SNe Ia belong to the young SNe Ia (Mannucci et al. 2008). The existence of the young and old populations of SNe Ia is also supported by some other observations (e.g., Aubourg et al. 2008; Totani et al. 2008).

The purpose of this paper is to study SN Ia birthrates and delay times from different progenitor models, and compare them with observations. We describe the binary population synthesis (BPS) approach for the different progenitor models in Section 2 and present the BPS results in Section 3. Section 4 ends the paper with a discussion.
2. Binary population synthesis

In order to investigate SN Ia birthrates and delay times, we performed a series of Monte Carlo simulations in the BPS study. In each simulation, we followed the binary evolution via the rapid binary evolution code developed by Hurley et al. (2002).

2.1. Common envelope in binary evolution

The progenitor of an SN Ia is a close WD binary, which has most likely emerged from the common envelope (CE) evolution of a giant binary. During the binary evolution, the primordial mass ratio (primary to secondary) is crucial for the mass transfer. If it is larger than a critical mass ratio, $q_c$, the mass transfer may be dynamically unstable and a CE develops. The mass ratio $q_c$ varies with the evolutionary state of the primary at the onset of the Roche lobe overflow (RLOF) (e.g., Han et al. 2002). In this study we adopt $q_c = 4.0$ when the primary is in the main-sequence stage or Hertzsprung gap. This value is supported by detailed binary evolution studies (e.g., Han et al. 2000). If the primary is on the first giant branch or asymptotic giant branch stage, we use

$$q_c = [1.67 - x + 2(M_{P1}^{cp})^5]/2.13,$$

where $M_{P1}^{cp}$ is the mass of the primary, $M_{P1}^{cp}$ is the core mass of the primary, and $x = d \ln R_{P1}^f/d \ln M_{P1}^i$ is the mass-radius exponent of the primordial primary and varies with composition. If the mass donor stars (primaries) are naked He giants, $q_c = 0.748$ based on eq. (1) (see Hurley et al. 2002 for details).

When a CE forms, embedded in the CE is a ‘new’ binary consisting of the dense core of the primary and the secondary. Owing to frictional drag within the envelope, the orbit of the ‘new’ binary decays and a large part of the orbital energy released in the spiral-in process is injected into the envelope. The CE ejection is still an open problem. Here, we use the standard energy equations (Webbink 1984) to calculate the output of the CE phase. The CE is ejected if

$$\alpha_{ce} \left( \frac{GM_{don}^{i} M_{acc}}{2a_i} - \frac{GM_{don}^{i} M_{acc}}{2a_f} \right) = \frac{GM_{don}^{i} M_{env}}{\lambda R_{don}},$$

where $\lambda$ is a structure parameter that depends on the evolutionary stage of the mass donor star, $M_{don}$ is the mass of the donor, $M_{acc}$ is the mass of the accretor, $a$ is the orbital separation, $M_{env}$ is the mass of the donor’s envelope, $R_{don}$ is the radius of the donor, and the indices i and f denote the initial and final values. The right side of the equation represents
the binding energy of the CE, while the left side shows the difference between the final and initial orbital energy, and \( \alpha_{ce} \) is the CE ejection efficiency (the fraction of the released orbital energy used to eject the CE). For this prescription of the CE ejection, there are two highly uncertain parameters (i.e., \( \lambda \) and \( \alpha_{ce} \)). As in previous studies, we combine \( \alpha_{ce} \) and \( \lambda \) into one free parameter \( \alpha_{ce}\lambda \) (Wang et al. 2009b).

2.2. The progenitor model of SNe Ia

Theoretically, there is a consensus that an SN Ia is the explosion and complete disintegration of a CO WD that has a mass close to the Chandrasekhar limit mass \( M_{Ch} \) (1.378 \( M_\odot \) in this work). We adopt two popular models for the progenitors of SNe Ia: the DD and SD models.

2.2.1. The DD model

For the DD model, SNe Ia arise from the merging of two close CO WDs that have a combined mass larger than or equal to the \( M_{Ch} \) (Webbink 1984; Han 1998). Both WDs are brought together by gravitational wave (GW) radiation on a timescale \( t_{GW} \) (Landau & Lifshitz 1971),

\[
t_{GW}(\text{yr}) = 8 \times 10^7 \text{(yr)} \times \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} P^{8/3}(\text{h}),
\]

where \( P \) is the orbital period in hours, \( t_{GW} \) in years and \( M_1, M_2 \) in \( M_\odot \).

The delay time from the star formation to the occurrence of an SN Ia is equal to the sum of the timescale on which the secondary star becomes a WD and the orbital decay time \( t_{GW} \). Here, we set the \( \alpha_{ce}\lambda = 1.5 \), which reproduces the number of the double-degenerate objects in the Galaxy (Hurley et al. 2002).

2.2.2. The SD model

For the SD model, we considered the WD + He star, WD + MS and WD + RG channels in this paper. Take the WD + He star channel for example, we followed the evolution of \( 1 \times 10^7 \) sample binaries from the star formation to the formation of the WD + He star systems. We assumed that, if the parameters of a CO WD + He star system at the onset of the RLOF are located in the SN Ia production regions in the \((\log P^i, M_2^i)\) plane (Figure 8 of Wang et al. 2009a), where \( P^i \) and \( M_2^i \) are the orbital period and the mass of the He
companion star at the onset of the RLOF, respectively, an SN Ia is produced. Note that, the method of the BPS study for the WD + MS and WD + RG channels is similar to that of the WD + He star channel. For the SN Ia production regions of these two channels, see Wang, Li & Han (2010). Here, we set the \( \alpha_{ce} \lambda = 0.5 \), which is our standard model for the formation of these SD channels (Wang, Li & Han 2010).

2.3. Basic parameters for Monte Carlo simulations

In the BPS study, the Monte Carlo simulation requires as input the initial mass function (IMF) of the primary, the initial mass-ratio distribution, the distribution of initial orbital separations, the eccentricity distribution of binary orbit, and the star formation rate (SFR) (Wang et al. 2009b; Han 2008a,b).

(1) The IMF of Miller & Scalo (1979) is adopted. The primordial primary is generated according to the formula of Eggleton et al. (1989),

\[
M_1^P = \frac{0.19X}{(1 - X)^{0.75} + 0.032(1 - X)^{0.25}} M_\odot,
\]

where \( X \) is a random number uniformly distributed in the range \([0, 1]\) and \( M_1^P \) is the mass of the primordial primary, ranging from 0.1 \( M_\odot \) to 100 \( M_\odot \).

(2) The initial mass-ratio distribution of the binaries, \( q' \), is quite uncertain for binary evolution. For simplicity, we take a constant mass-ratio distribution,

\[
n(q') = 1, \quad 0 < q' \leq 1,
\]

where \( q' = M_2^P / M_1^P \).

(3) We assume that all stars are members of binaries and that the distribution of separations is constant in \( \log a \) for wide binaries, where \( a \) is separation and falls off smoothly at a small separation

\[
a \cdot n(a) = \begin{cases} 
\alpha_{sep} (a/a_0)^m, & a \leq a_0, \\
\alpha_{sep}, & a_0 < a < a_1,
\end{cases}
\]

where \( \alpha_{sep} \approx 0.07, a_0 = 10 R_\odot, a_1 = 5.75 \times 10^6 R_\odot = 0.13 \text{ pc} \) and \( m \approx 1.2 \). This distribution implies that the numbers of wide binaries per logarithmic interval are equal, and that about 50 per cent of stellar systems have orbital periods less than 100 yr (Han et al. 1995).

(4) A circular orbit is assumed for all binaries. The orbits of semidetached binaries are generally circularized by the tidal force on a timescale which is much smaller than the nuclear timescale. Also, a binary is expected to become circularized during the RLOF.
(5) We simply assume a constant SFR over the past 15 Gyr, or, alternatively, a delta function, i.e., a single starburst. In the case of the constant SFR, we calibrate the SFR by assuming that one binary with a primary more massive than $0.8 \, M_\odot$ is formed annually (see Han et al. 1995; Hurley et al. 2002). From this calibration, we can get $\text{SFR} = 5 \, M_\odot \, \text{yr}^{-1}$. For the case of the single starburst, we assume a burst producing $10^{11} \, M_\odot$ in stars. In fact, a galaxy may have a complicated star formation history. We choose only these two extremes for simplicity. A constant SFR is similar to the situation of spiral galaxies (e.g., Han & Podsiadlowski 2004), while a delta function to that of elliptical galaxies or globular clusters.

3. The results of binary population synthesis

3.1. The birthrates of SNe Ia

We performed four sets of simulations with metallicity $Z = 0.02$ and $\text{SFR} = 5 \, M_\odot \, \text{yr}^{-1}$ to systematically investigate Galactic birthrates of SNe Ia for the DD and SD models, where the SD model includes the WD + He star, WD + MS and WD + RG channels (see Figure 1). We find the birthrate from the DD model $\sim 2.9 \times 10^{-3} \, \text{yr}^{-1}$, only slightly lower than the birthrate inferred from observations (i.e., $3-4 \times 10^{-3} \, \text{yr}^{-1}$; Cappellaro & Turatto 1997), while the total birthrates from the SD models can only account for about $1/2 - 2/3$ of the observations, where the birthrate from the WD + He star channel $\sim 0.3 \times 10^{-3} \, \text{yr}^{-1}$, the WD + MS channel $\sim 1.8 \times 10^{-3} \, \text{yr}^{-1}$ and the WD + RG channel $\sim 3 \times 10^{-5} \, \text{yr}^{-1}$.

The SN Ia birthrate in galaxies is the convolution of the distribution of the delay times (DDT) with the star formation history (SFH):

$$\nu(t) = \int_{0}^{t} SFR(t - t') DDT'(t')dt', \tag{7}$$

where the $SFR$ is the star formation rate, and $t'$ is the delay times of SNe Ia. Due to a constant SFR adopted in this paper, the SN Ia birthrate $\nu(t)$ is only related to the $DDT'$, which can be expressed by

$$DDT(t) = \begin{cases} 
0, & t < t_1, \\
DDT'(t), & t_1 \leq t \leq t_2, \\
0, & t > t_2,
\end{cases} \tag{8}$$

where $t_1$ and $t_2$ are the minimum and maximum delay times of SNe Ia, respectively, and the $DDT'$ is the distribution of the delay times between $t_1$ and $t_2$. If $t$ is larger than $t_2$, eq. (7) can be written as

$$\nu(t) = SFR \int_{t_1}^{t_2} DDT'(t')dt' = \text{constant}. \tag{9}$$
Therefore, the SN Ia birthrates shown in Figure 1 seem to be completely flat after the first rise.

3.2. The delay times of SNe Ia

Figure 2 displays the evolution of SN Ia birthrates for a single starburst with a total mass of $10^{11} M_\odot$. In the figure we see that SNe Ia from the DD model have the delay times of $\sim 89$ Myr to 15 Gyr, which are close to the observational results from Totani et al. (2008). However, it is suggested that the DD model is likely to lead to an accretion-induced collapse rather than to an SN Ia (Nomoto & Iben 1985). Thus, the DD model is not supported theoretically. We also find that SNe Ia from the SD models have a wide distribution of the delay times, where the WD $+$ He star channel contributes to the SNe Ia with delay times shorter than 100 Myr, and the WD $+$ MS and WD $+$ RG channels to those with age longer than 1 Gyr (the WD $+$ MS channel also contributes to the SNe Ia with intermediate delay times $\sim 100$ Myr $-$ 1 Gyr). Note that, Chen & Li (2007) studied the WD $+$ MS channel by considering a circumbinary disk which extracts the orbital angular momentum from the binary through tidal torques. This study also provides a possible way to produce such old SNe Ia ($\sim 1$ $-$ 3 Gyr).

The SD model is currently a favorable progenitor model of SNe Ia. The distribution of the delay time from the SD models is similar to that derived from observations by Mannucci et al. (2006), except that the peak value of young population is smaller than that in Mannucci et al. (2006). The WD $+$ He star channel produces 14 per cent of all SNe Ia, which constitutes the weak bimodality as suggested by Mannucci et al. (2008). The results from the SD models seem to be slightly smaller than those in Totani et al. (2008). However, given the high possibility of errors in the observation by Totani et al. (2008), our results are close to observations.

4. Discussion

In our BPS studies, we assumed that all stars are in binaries and about 50 per cent of stellar systems have orbital periods less than 100 yr. In fact, this is known to be a simplification. The binary fractions may depend on metallicity, environment and spectral type. If we adopt 40 per cent of stellar systems with orbital periods below 100 yr by adjusting the parameters in eq. (6), we estimate that the Galactic SN Ia birthrate from the DD model will decrease to be $\sim 2.3 \times 10^{-3}$ yr$^{-1}$, the WD $+$ He star channel $\sim 0.24 \times 10^{-3}$ yr$^{-1}$, the WD
Hachisu et al. (2008) investigated new evolutionary models for SN Ia progenitors, introducing the mass-stripping effect on a MS or a slightly evolved companion star by winds from a mass-accreting WD. Though the model offers a possible way to produce young SNe Ia, the model depends on the efficiency of the mass-stripping effect. We also find that the model produces very few young SNe Ia by a detailed BPS approach. Thus, we consider the WD + He star channel as a main contribution to the young population of SNe Ia, possible the whole young population.

The Galactic SN Ia birthrate from the WD + RG channel is $\sim 3 \times 10^{-5}$ yr$^{-1}$, which is low compared with observations. Thus, SNe Ia from this channel may be rare. However, further studies on this channel are necessary, since this channel may explain some SNe Ia with long delay times. RS Oph and T CrB, both recurrent novae are probable SN Ia progenitors and belong to the WD + RG channel (e.g. Belczyński & Mikolajewska 1998; Hachisu et al. 1999, 2007). Detecting Na I absorption lines with low expansion velocities indicates that the companion of the progenitor of SN 2006X may be an early RG star (Patat et al. 2007). We note that a symbiotic star with aspherical stellar wind may also provide a way for the evolution of the WD + RG systems towards SNe Ia (Lü et al. 2009).

Provided that the DD model can produce SNe Ia, an explosion following the merger of two WDs would leave no remnant, while the companion star in the SD model would survive and potentially be identifiable (Wang & Han 2009). Thus, it will be a promising method to test different SD models of SNe Ia by identifying their surviving companions.

The young and old populations of SNe Ia may have an effect on models of galactic chemical evolution, since they would return large amounts of iron to the interstellar medium much earlier or later than previously thought. In future investigations, we will explore the detailed influence of SNe Ia on the chemical evolution of stellar populations.

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Fig. 1.— Evolution of Galactic SN Ia birthrates for a constant star formation rate ($Z = 0.02$, SFR = $5 \, M_\odot \, yr^{-1}$). The key to the line-styles representing different progenitor models is given in the upper left corner.

Fig. 2.— Similar to Figure 1, but for a single starburst with a total mass of $10^{11} \, M_\odot$. The observational points are from Totani et al. (2008)\cite{21}. 

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