Why Are Peculiar Type Ia Supernovae More Likely to Show the Signature of a Single-degenerate Model?

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Received 2018 January 2; revised 2018 February 19; accepted 2018 February 20; published 2018 March 7

Abstract

Although Type Ia supernovae (SNe Ia) show their importance in many astrophysical fields, their exact progenitor nature is still unclear. A basic method to distinguish the different progenitor models is to search the signal from the single-degenerate (SD) model, e.g., the signal for the existence of a nondegenerate companion before or after supernova explosion. Observationally, some SNe Ia show such signals, while the others do not. Here, we propose a universal model to explain these observations based on the spin-up/spin-down model, in which a white dwarf (WD) will experience a spin-down phase before supernova explosion, and the spin-down timescale is determined by its initial mass, i.e., the more massive the initial WD, the shorter the spin-down timescale and then the more likely the SN Ia is to show the SD signature. Therefore, our model predicts that the SNe Ia from hybrid carbon–oxygen–neon WDs are more likely to show the SD signature observationally, as some peculiar SNe Ia showed.

Key words: ISM: supernova remnants – supernovae: general – white dwarfs

1. Introduction

Although Type Ia supernovae (SNe Ia) show their importance in many astrophysical fields, e.g., as standard candles to measure cosmological parameters (Riess et al. 1998; Perlmutter et al. 1999), a decades-long debate is endless on their progenitors (Hillebrandt & Niemeyer 2000; Wang & Han 2012). A consensus has been achieved that the thermonuclear explosion of a carbon–oxygen white dwarf (CO WD) in a binary system produces an SN Ia (Hoyle & Fowler 1960). Based on the companion nature of the mass accreting WDs, the progenitor models of SNe Ia were divided into two basic scenarios: one is the single-degenerate (SD) model where the companion is a normal star, i.e., a main-sequence or a slightly evolved star (WD+MS), a red giant star (WD+RG) or a helium star (WD+He star), the other involving the merger of two CO WDs is the double degenerate (DD) model (Wang & Han 2012; Maoz et al. 2014).

A basic method to distinguish the different models is to search the signature from the nondegenerate companion before or after supernova explosion, e.g., to search the surviving companion in a supernova remnant, to detect the UV excess from the interaction between supernova ejecta and the companion or to detect the progenitor system directly from the archival images before supernova explosion (Wang & Han 2012; Maoz et al. 2014). Many efforts are performed to search such signals, in which some clearly show the signals (Foley et al. 2014; McCully et al. 2014; Cao et al. 2015), while the others do not (Li et al. 2011a; González Hernández et al. 2012; Kerzendorf et al. 2014; Olling et al. 2015). The simplest explanation is that some SNe Ia originate from the SD systems, and the others are from the DD ones. However, an interesting puzzle is that the SNe Ia exhibiting the companion signal tend to be the subluminous objects with low ejecta velocities, e.g., SN 2008ha, SN 2012Z, and iPTF14atg (Foley et al. 2014; McCully et al. 2014; Cao et al. 2015), which are classified as peculiar SNe Ia (SN 2002cx-like or SN 2002es-like objects, Li et al. 2003; Ganeshalingam et al. 2012), although some normal SNe Ia also show the UV excess from the collision between supernova ejecta and the companion, e.g., SN 2012cg and 2017cbv (Marion et al. 2016; Hosseinzadeh et al. 2017). On the contrary, the SNe Ia without companion signals tend to be normal SNe Ia, e.g. SN 1006, SN 2011fe, KSN 2012a, and KSN 2011b (Li et al. 2011a; Olling et al. 2015; Katsuda 2017). However, it must be emphasized that SN 2012cg and 2017cbv have a large binary separation at the moment of supernova explosion (Marion et al. 2016; Hosseinzadeh et al. 2017), and then are very likely to have relatively massive initial CO WDs since the more massive the initial WD, the more likely to explode in a large binary separation for a SN Ia according to detailed binary evolution calculations (e.g., Figure 12 in Meng & Podsiadlowski 2017).

Another strong piece of evidence favoring the SD model is the detection of circumstellar material (CSM) in the spectrum of SNe Ia (Hamuy et al. 2003; Patat et al. 2007; Sternberg et al. 2011; Dilday et al. 2012). The SNe Ia showing the strong CSM signal are classified as SNe Ia-CSM (Silverman et al. 2013). Both SN Ia-CSM- and SN 2002cx-like objects present spectra similar to SN 1991T and originate from young populations (Foley et al. 2013; Silverman et al. 2013). The overabundance of 1991T-like events also favors SD systems with significant mass loss before supernova explosion, even as high as ~10^-5 M_s, yr^-1 (Fisher & Jumper 2015; Katsuda et al. 2015), where the high mass-loss rate indicates a massive initial WD (e.g., Figure 4 in Meng & Podsiadlowski 2017). Considering that SN 2002cx-like and SN Ia-CSM objects share some common properties and the explosions of hybrid carbon–oxygen–neon (CO Ne) WDs appear rather heterogeneous, Meng & Podsiadlowski (2018) suggested that both subclasses could originate from the SD systems with hybrid CO Ne WDs. Although it cannot be completely excluded that the both subtypes have different origins, their model may reproduce the number ratio of SN Ia-CSM to SN 2002cx-like objects and the total contribution of the peculiar SNe to all SNe Ia. This suggestion is based on a new-version SD model, i.e., the...
common envelope wind model (Meng & Podsiadlowski 2017), where the CE mass distribution at the moment of supernova explosion is double peaked. The SNe Ia-CSM correspond to those with massive CE, while 2002cx-like SNe are from those exploding in less massive or no CE. Meng & Podsiadlowski (2018) suggest that the different explosion environment is the main reason why 2002cx-like and SN Ia-CSM objects seem quite different. In addition, the different cooling times of the WDS before accretion occurring for two subclasses could also play a key role in their different properties (see the discussions in Meng & Podsiadlowski 2018). In particular, the double peak CE mass distribution provides a potential explanation for the fact that no transitional event between SN 2002cx-like and SN Ia-CSM objects is discovered. Although arguments exist on whether or not a hybrid CONe WD may form and carbon ignition may occur in the hybrid WD, the chemical evolution of dwarf spheroidal galaxies may even provide some indirect support for their explosion (Lecoanet et al. 2016; Brooks et al. 2017; Cescutti & Kobayashi 2017).

Compared with CO WDs, CONe WDs are relatively massive (Chen et al. 2014), as required by the normal SNe Ia with the SD signal, e.g., SN 2012cg and 2017cbv. However, the environment around the normal SNe Ia tends to be clear, e.g., SN 2011fe and SN 2014J, and then these SNe Ia are proposed to be from the DD systems (Patat et al. 2013; Pérez-Torres et al. 2014). According to the above discussion, an interesting question arises, i.e., why do the SNe Ia with the SD signals tend to have massive initial WDs, while those proposed to be from the DD systems tend to be normal SNe Ia? May such a question be answered under a universal frame? Here, we investigate these questions and show that a universal frame is possible in principle.

In Section 2, we describe our method, and present the calculation results in Section 3. We show discussions and our main conclusions in Section 4.

2. Method

To explain why no surviving companion is found in supernova remnants, e.g., SNR 0509–67.5 (Schaefer & Pagnotta 2012), the spin-up/spin-down model is proposed, in which the WD is spun up by accretion, and must experience a spin-down phase before it explodes as an SN Ia (Di Stefano et al. 2011; Justham 2011). Then, the SNe Ia may not reveal the SD signature for a long spin-down timescale, which hints at a universal explanation of the above observational facts. However, there are many uncertainties on the model theoretically: (1) What is the fraction of the angular momentum of the accreted material to transfer to the accreting WD? (2) What is the mechanism to lose the angular momentum for a nonaccreting WD? (3) How long is the spin-down timescale, and (4) How is the unaccreted material ejected from the system? Since the method here is just based on the conservation of angular momentum, these uncertainties cannot significantly affect our basic conclusion.

The spin-down timescale denotes a delay time of a rapidly rotating WD from an initial fast rotation down to a critical angular velocity, and its exact value is quite uncertain (Di Stefano & Kilic 2012; Meng & Podsiadlowski 2013). However, whether a property from the SD model is observed or not heavily depends on the spin-down timescale. Since the timescale is determined by the initial angular velocity of the WD at the onset of the spin-down phase, we may use the initial angular velocity to represent the timescale. The angular velocity is dependent on the accretion history of the WD. The angular momentum of the material accreted along the equator of a WD is determined by

$$dJ = dmR_{WD}^2\omega_K,$$

where $R_{WD}$ is the radius of the WD and $\omega_K$ is the Keplerian angular frequency at the surface of the WD:

$$\omega_K = \left(\frac{GM_{WD}}{R_{WD}^3}\right)^{1/2}.$$

The WD radius is determined by

$$R_{WD} = 0.0115\left(\frac{M_{Ch}}{M_{WD}}\right)^{2/3} - \left(\frac{M_{WD}}{M_{Ch}}\right)^{2/3} R_\odot,$$

as in Tout et al. (1997), where $M_{Ch}$ is the Chandrasekhar mass. We assume that most SNe Ia explode at the same mass $M_{SN}^{WD} = 1.4 M_\odot$, which is upheld by both observations and theory (Scalzo et al. 2014; Wang et al. 2014). However, the angular momentum obtained by the accreting WD is probably much lower than that by Equation (1), e.g., taking away via nova explosion, or accreting by a CE rather than by a Keplerian disk (e.g., Meng & Podsiadlowski 2017). Then, the total angular momentum obtained by the accreting WD may be expressed by

$$\Delta J = \int_{M_{WD}}^{M_{SN}^{WD}} \alpha dJ = \int_{M_{WD}}^{M_{SN}^{WD}} \alpha R_{WD}^2\omega_K dm,$$

where $\alpha$ is a parameter much lower than 1, which indicates that the accreted material carries enough angular momentum to spin-up the WD. To maintain the final angular velocity to be smaller than Keplerian angular velocity, we take $\alpha = 0.003$ rather arbitrarily. Then, the final angular momentum of the WD after the accretion phase is

$$J_f = I_{WD}^{SN}\omega_f = \Delta J,$$

where $I_{WD}^{SN}$ is the moment of inertia at $M_{SN}^{WD} = 1.4 M_\odot$, and $\omega_f$ is angular frequency. We assume that $I_{WD}^{SN}$ is not dependent on the $\omega_f$, i.e., it is a constant for all rapidly rotating WDs of $M_{SN}^{WD} = 1.4 M_\odot$. The moment of inertia is parameterized with a structural constant $\beta$

$$I_{WD}^{SN} = \frac{2}{5}\beta M_{SN}^{WD} R_{WD}^2.$$

Here, we take $\beta = 0.27$ (Ilkov & Soker 2012). Then,

$$\omega_f = \frac{\Delta J}{I_{WD}^{SN}}.$$

We take $\omega_f$ as the initial value of angular velocity at the onset of the spin-down phase. At the spin-down phase, a rigid rotating WD may lose its rotational kinetic energy by magnetodipole radiation or gravitational wave radiation, or even magnetic braking. Here, we use $\omega_f$ to represent the rotational kinetic energy since $I_{WD}^{SN}$ is assumed to be a constant.
3. Result

3.1. The Rotational Kinetic Energy

In Figure 1, we show the rotational kinetic energy of a WD with its initial mass at the onset of the spin-down phase. As expected, the rotational kinetic energy is heavily dependent on the initial WD’s mass. The rotational kinetic energy of a WD with $M'_{\text{WD}} = 0.8 M_\odot$ is 20 times higher than that of a WD with $M'_{\text{WD}} = 1.3 M_\odot$, where 0.8 $M_\odot$ is the most probable value and 1.3 $M_\odot$ is the maximum mass for a WD to produce an SN Ia (Chen et al. 2014). At present, the exact mechanism losing the rotational kinetic energy is still unclear. For magnetodipole radiation, our result implies that the spin-down timescale for a WD with $M'_{\text{WD}} = 0.8 M_\odot$ may be more than 100 times as long as that of a WD with $M'_{\text{WD}} = 1.3 M_\odot$, where the exact times depend on the critical angular velocity triggering the thermonuclear explosion (Ilkov & Soker 2012).

If the spin-down timescale is long enough, the SD signal will be erased completely; otherwise, the SD signal will be expected. The spin-down timescale is determined by the initial angular velocity of a WD at the onset of the spin-down phase, and then by the initial WD mass as shown in Figure 1. In other words, the spin-down timescale for a massive initial WD is shorter than a less massive initial WD. Therefore, the more massive the initial WD, the more likely the SN Ia is to show the SD signal.

3.2. The Proportion of SNe Ia with the SD Signal

As discussed above, the more massive the initial WD, the more likely the SN Ia is to show the SD signal. However, the proportion of SNe Ia that have a potential to show the signature would heavily depend on a threshold value of the spin-down timescale. Unfortunately, the threshold value for an SN Ia is completely unclear. Since different initial WD masses correspond to different spin-down timescales, we may use the different initial WD masses to represent the different threshold values, and then study how the proportion of SNe Ia with the SD signal relies on the threshold value. Following the model grids in Meng & Podsiaiowski (2017, 2018), we performed two binary population synthesis (BPS) calculations, where the method for the BPS calculations is similar to that in Meng & Podsiaiowski (2017, 2018). Here, the WDs for SNe Ia include CO and hybrid CONe WDs. In Figure 2, we show the proportion as a function of the initial WD mass. As expected, the percentage decreases with $M'_{\text{WD}}$, i.e., the shorter the threshold value for the spin-down timescale, the smaller the proportion of SNe Ia with the SD signal is. In addition, the percentage sharply decreases around $M'_{\text{WD}} \approx 0.8 M_\odot$, which means that the distribution of the WDs for SNe Ia peaks at $M'_{\text{WD}} \approx 0.8 M_\odot$. This implies that the threshold value of the spin-down timescale would be shorter than that represented by $M'_{\text{WD}} = 0.9 M_\odot$, since most SNe Ia do not show the SD signal.

However, it should be emphasized that not all SNe Ia from massive initial WDs must show the SD signal. For example, some SNe Ia from massive initial WDs may have a very clear environment, or a less massive companion at the moment of supernova explosion (Meng & Podsiaiowski 2017). So, it will be very difficult to detect the CSM around such SNe Ia, or to detect the UV excess from the interaction between supernova ejecta and the companion. Moreover, the UV excess is highly view-angel-dependent, which may significantly reduce the possibility further (Kasen 2010). Therefore, the proportion shown in Figure 2 is just a conservative upper limit.

As discussed in Section 1, the peculiar SNe Ia are more likely to show the SD signal, but the contribution of the peculiar SNe Ia to all SNe Ia is still uncertain (Li et al. 2011b; Foley et al. 2013). However, it is very possibly between 5% and 10% (Meng & Podsiaiowski 2018). In Figure 2, we also plot two horizontal lines to show 5% and 10%. Corresponding to the value of 10%, the initial WDs must be more massive than $\sim 1.03$ or $\sim 1.21 M_\odot$ relying on the CE ejection efficiency ($\alpha_{\text{CE}}$). 1.03 $M_\odot$ is close to the upper boundary for CO WDs (Chen et al. 2014). Compared with the SNe Ia from the CO WDs, those from the hybrid CONe WDs are more likely to show the SD signal for their higher initial mass. The SNe Ia with CONe WDs are proposed to present the properties of peculiar SNe Ia (Meng & Podsiaiowski 2014, 2018; Kromer et al. 2015). Such a proposal obtains further support from the
fact that peculiar SNe Ia have a higher probability of showing the SD signals.

In addition, our results do not exclude SNe Ia from massive CO WD to show the SD signal since the exact proportion of SNe Ia with the SD signal is unclear. If 15% of SNe Ia have the potential to show the SD signal, the threshold value of the initial WD mass is $\sim 0.9 M_\odot$ ($\alpha_{CE} = 3.0$) or $1.15 M_\odot$ ($\alpha_{CE} = 1.0$), which is a value larger than that of most SNe Ia. This may explain why some normal SNe Ia exhibit the UV excess from the interaction between supernova ejecta and the companion, e.g., it is very possible that normal SN 2012cg and 2017cbv will have massive initial WDs (Marion et al. 2016; Hosseinzadeh et al. 2017).

4. Discussions and Conclusions

In this paper, we propose that whether an SN Ia will reveal the SD signature is determined by its initial WD mass, based on the spin-up/spin-down model. A massive WD only needs to accrete a small amount of the material to reach the Chandrasekhar limit, and then obtains a small amount of angular momentum. Such a WD will take a shorter spin-down timescale for a slow rotation to get the condition triggering an SNe Ia. Thus, the more massive the initial WD, the more likely the SD signal is to be observed. As shown in Figure 2, the SNe Ia from hybrid CONe WDs are more likely to show the SD signal. Such SNe Ia are proposed to present the properties of the SN 2002cx-like and SN Ia-CSM events (Meng & Podsiadlowski 2014; Kromer et al. 2015; Meng & Podsiadlowski 2018). This may explain why peculiar objects are more likely to show the SD signal. Even though the SNe Ia are normal, it is still more possible to show the SD signal for those with massive initial WDs, e.g., SN 2012cg and 2017cbv (Marion et al. 2016; Hosseinzadeh et al. 2017).

Observationally, most SNe Ia do not show the SD signal, which may also be explained by our suggestion. In Figure 2, most SNe Ia have an initial CO WD with $< 0.9 M_\odot$. If their spin-down timescale is long enough, the properties predicted by the SD model will be erased, and then most of the SNe Ia will not show the SD signal. Our results imply that the threshold value of the spin-down value for the SD signal corresponds to the one with $M_{WD} \geq 0.9 M_\odot$. Based on a semi-empirical method, Meng & Podsiadlowski (2013) found that the spin-down timescale is shorter than a few $10^7$ years, which is long enough for the companion to become too dim to be detected in the supernova remnant (Di Stefano & Kilić 2012). At the same time, Meng & Podsiadlowski (2018) noticed that a spin-down timescale of $\sim 10^6$ years is favored to show the SD signal for the SNe Ia from the CONe WDs.

In this paper, the method to calculate $\omega_f$ is very simple, and we do not solve the structure of the rapidly rotating WD and follow the exact accretion history in detail. Then, the exact $\omega_f$ value of a WD may be different from that shown in Figure 1. However, the trend of $\omega_f$ with the initial WD mass will still hold, since our basic idea is just from the conservation of angular momentum. In addition, we assume that all SNe Ia explode at $M_{WD} \sim 1.4 M_\odot$, while a rapidly rotating WD may exceed the mass. It has been proved that, generally, the higher the initial mass of a WD, the more massive the final mass is at the onset of the spin-down phase and then the shorter the spin-down timescale (Hachisu et al. 2012; Wang et al. 2014a). Therefore, our assumption here could weaken the effect of the initial mass on the spin-down timescale, but does not change the trend. Moreover, the distribution of the initial WD masses is based on the WD+MS channel, where the distribution peaks at $M_{WD} \sim 0.8 M_\odot$ (Meng & Podsiadlowski 2017, 2018), and the channels with red giant (WD+RG) and helium star (WD+He star) companions are not included in Figure 2. SN iPTF14atg is probably from the WD+RG channel and SN 2012Z is from the WD+He star channel (McCully et al. 2014; Cao et al. 2015). However, the distribution of the initial WD masses from WD + RG channel is similar to that from the WD+MS channel (Chen et al. 2011). The peak of the distribution from the WD + He star channel is higher than that from the WD+MS channel, i.e., at $M_{WD} \sim 1.0 M_\odot$, but the SNe Ia from the WD + He star channel may only contribute to all SNe Ia by $\sim 10\%$. Therefore, our results may not be significantly affected by our simple treatments, and our basic conclusion still holds. In particular, the peculiar SN 2012Z also fulfills our suggestion, i.e., the supernova is very likely derived from a massive hybrid CONe WD from a binary evolution point of view (Wang et al. 2014b).

In summary, according to the spin-up/spin-down model, we propose a universal explanation on why peculiar SNe Ia are more likely to show the signature predicted by the SD model, while normal SNe Ia are not. We suggest that this is derived from the different initial masses and different initial chemical composition of the WDs. Most SNe Ia originate from the CO WDs, and these SNe Ia experience a relatively long spin-down phase before supernova explosion, which erases the SD signal. On the contrary, the peculiar objects are suggested from the massive CONe WDs, and these SNe Ia experience a shorter spin-down timescale than those from the CO WDs before supernova explosion. A short spin-down timescale means that these SNe Ia are more likely to show the properties expected from the SD model. In particular, our model suggests that some normal SNe Ia from massive CO WDs can show the SD signal.

This work was supported by the NSFC (Nos. 11473063, 11522327, 11390374, 11521303, and 11733008), the Yunnan Foundation (Nos. 2015HB096, 11733008), the CAS light of West China Program and CAS (No. KJZD-EW-M06-01), Z.H. thanks the support by the Science and Technology Innovation Talent Programme of the Yunnan Province (No. 2013HA005).

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