The Effect of Metallicity on the Delay-Time Distribution of Type Ia Supernova

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Abstract

Measuring the delay-time distribution (DTD) of type Ia supernova (SNe Ia) is an important way to constrain the progenitor nature of SNe Ia. Recently, Strolger et al. (2010, ApJ, 713, 32, hereafter SDR10) obtained a very delayed DTD, which is much different from other measurements. They suggested that metallicity could be the origin of their delayed DTD. In this paper, we show the effect of metallicity on the DTD of SNe Ia from single-degenerate models (including WD + MS and WD + RG channels). Via a binary population synthesis approach, we find that the DTD from a low-metallicity population is significantly delayed compared with that from a high-metallicity one. In addition, we also find that a substantial fraction of SNe Ia have a delay time shorter than 1 Gyr, and the fraction of SNe Ia with short delay times increases with the metallicity, i.e., about 35% for $Z = 0.001$, while more than 70% for $Z = 0.02$. These results would help to qualitatively explain the result of SDR10. Furthermore, we noticed that the contribution of the WD + RG channel from the low-metallicity population is higher than that from the high-metallicity one. However, we could not quantitatively obtain a DTD consistent with the results of SDR10 by changing the metallicity. As a consequence, metallicity may partly contribute to the DTD of SNe Ia, and should therefore be carefully checked when one derives the DTD of SNe Ia from observations.

Key words: stars: binaries: general — stars: supernovae: general — stars: white dwarfs

1. Introduction

Although Type Ia supernovae (SNe Ia) are very important in cosmology (Riess et al. 1998; Perlmutter et al. 1999), the exact nature of their progenitors is still unclear (Hillebrandt & Niemeyer 2000; Leibundgut 2000; Parthasarathy et al. 2007). There is a consensus that SNe Ia results from the thermonuclear explosion of a carbon–oxygen white dwarf (CO WD) in a binary system (Hoyle & Fowler 1960). According to the nature of the companions of mass-accreting WDs, two basic scenarios for the progenitors of SN Ia have been discussed over the last three decades. One is the single degenerate (SD) model (Whelan & Iben 1973; Nomoto et al. 1984), i.e., the companion is a main-sequence or a slightly evolved star (WD + MS), or a red-giant star (WD + RG) or a helium star (WD + He star) (Li & van den Heuvel 1997; Hachisu et al. 1999; Langer et al. 2000; Han & Podsiałdowski 2004; Chen & Li 2007; Meng et al. 2009, hereafter MCH09; Liu et al. 2009; Wang et al. 2009, 2010). The other is the double-degenerate (DD) model, i.e., the companion is another WD (Iben & Tutukov 1984; Webbink 1984). Measuring the delay-time distribution (DTD, delay time is the elapsed time between primordial system formation and explosion as a SN Ia event) is a very important way to distinguish between the different progenitor systems. Recently, using the high-redshift SNe Ia sample ($0.2 < z < 1.8$) from the Hubble Space Telescope ACS imaging of the GOODS North and South fields, Stronger, Dahlen, and Riess (2010, hereafter SDR10) showed a significantly delayed DTD that is confined to 3–4 Gyr, which is difficult to resolve with any intrinsic DTD. This result confirmed their previous findings (Strolger et al. 2004). However, they also noticed that this result is mainly motivated by a decline in the number of SNe Ia at $z > 1.2$. Their sub-samples with low redshift ($z < 1.2$) showed plausible DTDs dominated by SNe Ia with short delay times. The difference between their low-$z$ and high-$z$ results may be partly explained by the fact that a substantial fraction of $z > 1.2$ supernova may be obscured by dust. However, the DTD derived by SDR10 may be dominated by systematic errors, in particular due to uncertainties in the star-formation history (SFH: Forster et al. 2006). The inferred delay time is strongly dependent on the peak in the assumed SFH, and none of the popular progenitor models under consideration can be ruled out with any significant degree of confidence (see also Oda et al. 2008; Valiante et al. 2009).

Moreover, the results of SDR10 are inconsistent with many low and moderate redshift measurements, which showed that most SNe Ia have delay times of between 0.3 and 2 Gyr (Schawinski 2009), and that there are also SNe Ia with very long delay times (older than 10 Gyr inferred from SNe Ia in elliptical galaxies in the local universe, Mannucci et al. 2005) or extremely short delay times (shorter than 0.1–0.3 Gyr, Mannucci et al. 2006; Schawinski 2009; Raskin 2009). Based on some observations, i.e., a strong enhancement of the SN Ia birth rate in radio-loud early-type galaxies, the strong dependence of the SN Ia birth rate on the colors of the host galaxies, and the evolution of the SN Ia birth rate with redshift (Della Valle et al. 2005; Mannucci et al. 2005; Strolger et al. 2004), Mannucci et al. (2006) suggested a bimodal DTD,
in which some of the SNe Ia explode soon after starburst with a delay time less than 0.1–0.5 Gyr (‘prompt’ SNe Ia: Schawinski 2009; Raskin 2009), while the rest have a much wider distribution with a delay time of about 3 Gyr (‘tardy’ SNe Ia). In theory, the bimodal DTD may be constructed from detailed binary population synthesis (Meng & Yang 2010a, hereafter MY10). However, the excess of SNe Ia in radio galaxies is the only observation that strongly indicates an extremely large amount of the prompt population, and hence is distinct from the longer delay time population (see Mannucci et al. 2006), but this excess is not supported by a more recent observation (Graham et al. 2010). By comparing with the host galaxy color, some authors proposed a simple two-component model, A + B model, which may be a variation of the bimodal DTD. (Scannapieco & Bildsten 2005; Sullivan et al. 2006; Brandt et al. 2010). Recently, more observational evidence has shown that the DTD of SNe Ia follows the power-law form of \( t^{-1} \), which is much different from the results of SDR10. The power-law form is even different from the bimodal model or the A + B model, which might indicate that the simple two-component model is an insufficient description for observational data (Totani et al. 2008; Maoz 2010; Maoz et al. 2010, 2011). Even via the same method as SDR10, i.e., a comparison between cosmic SFR evolution and SN Ia rate evolution, a \( t^{-1} \) DTD was also found to be in nice agreement with the observed data (Graur 2011). The DTD derived by SDR10 is well-confined to 3–4 Gyr, which is strongly inconsistent with those DTDs mentioned above, and only a small fraction belong to the “prompt” SNe Ia population, i.e., smaller than 10%. However, some low-redshift samples show the existence of prompt SNe Ia at a high confidence level, and the birth rate of the prompt component is much higher than that of the tardy SNe Ia (Aubourg et al. 2008; Maoz et al. 2011). Theoretically, short delay SNe Ia may also be produced by a WD + helium star and WD + MS channel (Wang et al. 2009; MY10).

Whatever, SDR10 suggested that the effect of metallicity could be one possible resolution for the disagreement between their discovery and low/moderate results. In this paper, we want to check whether changing the metallicity can create DTDs consistent with the results of SDR10, within the framework of the single-degenerate scenario.

In section 2, we simply describe our method, and present the calculation results in section 3. In section 4, we present discussions and our main conclusions.

2. Method

Recently, MY10 constructed a comprehensive single degenerate progenitor model for SNe Ia. In this model, the mass-stripping effect of optically thick wind (Hachisu et al. 1996) and the effect of a thermally unstable disk were included (Hachisu et al. 2008; Xu & Li 2009). The prescription of Hachisu et al. (1999) on WDs accreting hydrogen-rich material from their companions was applied to calculate the WD mass growth. The optically thick wind and the material stripped-off by the wind were assumed to take away the specific angular momentum of the WD and its companion, respectively. In MY10, both the WD + MS channel and WD + RG channel are considered, i.e., Roche lobe overflow (RLOF) begins at the MS or RG stage. The galactic birth rate of SNe Ia derived from that model is comparable with that from observations. In addition, this model may even explain some supernovae with low hydrogen mass in their explosion ejecta (Meng & Yang 2010b). MY10 calculated more than 1600 WD close binary evolutions, and showed the initial parameter space leading to SNe Ia in an orbital period–secondary mass (log \( P_i, M_2 \)) plane; these results may be conveniently used in a binary population synthesis code for obtaining the DTD of SNe Ia.

The delay time of a SN Ia from the SD model is mainly determined by the stellar evolutionary timescale of the secondary, and thus the secondary mass. This is to say that the DTD of SNe Ia is a function of the location of the parameter space in the (log \( P_i, M_2 \)) plane. However, this location is directly affected by the metallicity. For a system with a given initial WD mass and orbital period, the initial mass of the companion leading to SNe Ia increases with the metallicity, i.e., the upper boundary and lower boundary of the companion mass move to lower values along with a decrease of the metallicity (see the figure 4 in MCH09). Thus, the DTD of SNe Ia are affected by metallicity via companion mass. Between the two boundaries of the companion mass for SNe Ia, the lower boundary dominates the longer delay time of SNe Ia. The low boundary is mainly determined by the condition that the mass-transfer rate between a CO WD and its companion is higher than a critical value, which is the lowest accretion rate of a CO WD avoiding violent nova explosion, while the upper boundaries are mainly determined by dynamically unstable mass transfer and the strong hydrogen-shell flash. The mass-transfer rate for a given binary system is closely related to the metallicity, which is due to the correlation between the stellar structure and the metallicity (Umeda et al. 1999a; Chen & Tout 2007). Generally, the time-scale for mass transfer is the thermal time-scale, which increases with the metallicity. This leads to a higher mass-transfer rate for a low-metallicity system (Langer et al. 2000). Thus, low-mass companions with low metallicity are more likely to fulfill the constraint for mass transfer than those with high metallicity. A WD + MS system with low metallicity is therefore more likely to be the progenitor of a SN Ia (also see MCH09). On the other hand, a high mass-transfer rate means that a binary system with the same initial parameters, but low metallicity, will more possibly fulfill the condition of dynamical instability. Even though the mass transfer for the system is dynamically stable, the mass-transfer rate could be so high that most of the transferred material is lost from the system by the optically thick wind, and at the same time a large amount of hydrogen-rich material stripped off by the wind is lost from the companion envelope. The mass-transfer rate then sharply decreases to less than the critical value for avoiding the strong hydrogen-shell flash after mass-ratio inversion. As a consequence, the initial parameter space for SNe Ia moves to a lower companion mass with the decrease of metallicity (MCH09). For example, for a system with given initial WD mass and initial orbital period, the companion mass for \( Z = 0.001 \) is lower than that of \( Z = 0.02 \) by about 0.4 \( M_\odot \) (see also Chen & Li 2009).
In the present work, we did not calculate binary evolution for low metallicity; instead, we moved the parameter space for SNe Ia of $Z = 0.02$, given by MY10, to a lower companion mass by $0.4 M_\odot$, and assumed rather arbitrarily that the parameter space with a low companion mass is equivalent to that for $Z = 0.001$. To clarify what we did, we used the case of $M_{WD} = 1.00 M_\odot$ as an example (see figure 1). Since we only want to check whether the metallicity has an ability to create a DTD matching with the discovery of SDR10, this simple assumption is not unreasonable (see discussion in subsection 4.3).

To obtain the DTD of $Z = 0.001$, we have performed a series detailed Monte Carlo simulations via Hurley’s rapid binary evolution code (Hurley et al. 2000, 2002). In the simulations, if a binary system evolves to a WD + MS or WD + RG stage, and the system is located in the ($\log p^1$, $m^2$) plane for SNe Ia at the onset of RLOF; we assume that a SN Ia is produced. In simulations, we followed the evolution of $10^7$ sample binaries. The evolutional channel is described in MY10. As for MY10, we adopted the following input for the simulations: (1) A single starburst was assumed, $10^{11} M_\odot$ in stars are produced at one time. (2) The initial mass function of Miller and Scalo (1979) was adopted. (3) The mass-ratio distribution was taken to be constant. (4) The distribution of separations was taken to be constant in $\log a$ for wide binaries, where $a$ is the orbital separation. (5) A circular orbit was assumed for all binaries. (6) The common envelope (CE) ejection efficiency, $\alpha_{CE}$, which denotes the fraction of the released orbital energy used to eject the CE, was set to 1.0 or 3.0. (see MY10).

3. Result

In figure 2, we show the evolution of the birth rates of SNe Ia for a single starburst for different $\alpha_{CE}$ values and different metallicities. We can see from the figure that whatever the $\alpha_{CE}$, the DTDs of $Z = 0.001$ are significantly delayed compared with those of $Z = 0.02$. For $Z = 0.02$, SNe Ia mainly occur between 0.2 and 2 Gyr with a mean value of 0.89 Gyr after the burst, while they occur between 0.3 and 3.5 Gyr with a mean value of 1.94 Gyr for $Z = 0.001$. This is mainly derived from the low companion mass for low metallicity. As stated in Han and Podsiadlowski (2004) and MY10, we found that a high $\alpha_{CE}$ leads to a systematically later explosion time for $Z = 0.001$, because a high $\alpha_{CE}$ leads to wider WD binaries and, as a consequence, it takes a longer time for the secondary to evolve to fill its Roche lobe. As noticed by MCH09, the peak value of the DTD for low metallicity is lower than that for high metallicity and the WD + MS channel is the dominant channel for the peak value. However, the contribution of the WD + RG channel to SNe Ia for $Z = 0.001$ is higher than that for $Z = 0.02$, i.e., $1\% - 2\%$ for $Z = 0.02$, but $8.6\% - 16\%$ for $Z = 0.001$. Actually, MCH09 noticed that the WD + RG channel may be more common for low metallicity (see footnote 1 in MCH09).

We also checked the fraction of SNe Ia with short delay times, and found that a substantial fraction of SNe Ia have a delay time shorter than 1 Gyr, and the fraction of SNe Ia with short delay times increases with the metallicity, i.e., about 35% for $Z = 0.001$, while it is more than 70% for $Z = 0.02$.

4. Discussions and Conclusions

4.1. Comparison with Observations

Measuring the DTD of SNe Ia is an important way to constrain the nature of the progenitor of SNe Ia. SDR10 used data from the Hubble space telescope to confirm their previous results that the data are largely inconsistent with the progenitor scenarios with short delay time, which is difficult to explain with any intrinsic DTD. SDR10 suggested a possible resolution for their results, i.e., an environment such as metallicity may affect the progenitor mechanism efficiently, especially in the early universe. Our results given in this paper seem to support this suggestion because we found that low metallicity may significantly delay the DTD of SNe Ia. If the result obtained by SDR10 shows the real nature of the DTD of SNe Ia, the metallicity could be an indispensable factor that must be considered when studying the progenitors of SNe Ia. However, for
Thus, there are still a few progenitor stars formed at $z > 3$ that could contribute to SNe Ia with long delay times at $z \approx 1$–2.

3 The existence of an optically thick wind is in doubt for very low metallicity (Kobayashi et al. 1998).
included (see Wang et al. 2010). The effect of the thermally unstable disk affects not only the birth rate, but also the delay time. If this effect were not included, the birth rate and the delay time would decrease significantly, which might lead to a DTD that is also not consistent with the observation of SDR10.

Finally, we assume implicitly that the assumptions in MY10 are not affected by the metallicity. This assumption is rather arbitrary, since great efforts are necessary to support it. Fortunately, some previous studies showed that the influence of metallicity on the assumptions in the SD model could be neglected. For example, the critical accretion rate and the structure of WDs are almost not affected by the metallicity (Meng et al. 2006; Umeda et al. 1999a, 1999b). Our assumption might thus not be a serious problem.

In summary, this paper failed to obtain its stated goal: to create a DTD consistent with the measurement of the SDR10 metallicity based on a SD scenario. The metallicity may only partly resolve the long delay-time results of SDR10. However, when using the delay time derived from observations to constrain the progenitors of SNe Ia, the metallicity should be carefully checked.

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