THE DELAY TIME DISTRIBUTION OF TYPE Ia SUPERNOVAE AND THE SINGLE DEGENERATE MODEL

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ABSTRACT

We present a theoretical delay time distribution (DTD) of Type Ia supernovae on the basis of our new evolutionary models of single degenerate (SD) progenitor systems. Our model DTD has almost a featureless power law shape ($\propto t^{-n}$ with $n \approx 1$) for the delay time from $t \sim 0.1$ to 10 Gyr. This is in good agreement with the recent direct measurement of DTD. The observed featureless property of the DTD has been suggested to be favorable for the double degenerate (DD) scenario but not for the SD scenario. If the mass range of the companion star to the white dwarf (WD) were too narrow in the SD model, its DTD would be too limited around the companion’s main-sequence lifetime to be consistent with the observed DTD. However, this is not the case in our SD model that consists of the two channels of WD + RG (red giant) and WD + MS (main-sequence star). In these channels, the companion stars have a mass range of $\sim 0.9 - 3 M_\odot$ (WD+RG) and $\sim 2 - 6 M_\odot$ (WD+MS). The combined mass range is wide enough to yield the featureless DTD. We emphasize that the SD scenario should include two important processes: the optically thick winds from the mass-accreting WD and the mass-stripping from the companion star by the WD wind.

Subject headings: binaries: close — galaxies: evolution — stars: winds, outflows — supernovae: general

1. INTRODUCTION

Type Ia supernovae (SNe Ia) play the important roles in astrophysics as a standard candle to measure cosmological distances as well as the production site of a large part of iron group elements. However, the nature of SN Ia progenitors has not been clarified yet (e.g., Hillebrandt & Niemeyer 2000; Nomoto et al. 1997, 2000; Livio 2000). It has been commonly agreed that the exploding star is a carbon-oxygen white dwarf (C+O WD) and the observed features of SNe Ia are better explained by the Chandrasekhar mass model than the sub-Chandrasekhar mass model. However, there has been no clear observational indication as to how the WD mass gets close enough to the Chandrasekhar mass for carbon ignition; i.e., whether the WD accretes H/He-rich matter from its binary companion [single degenerate (SD) scenario] or two C+O WDs merge [double degenerate (DD) scenario].

It has been suggested that SNe Ia have a wide range of delay time from $t < 0.1$ Gyr to $t > 10$ Gyr (e.g., Mannucci et al. 2006). Here the delay time, $t$, is defined as the age at the explosion of the SN Ia progenitor from its birth. According to Mannucci et al. (2006), the present observational data of SNe Ia are best matched by a bimodal population of the progenitors, in which about 50 percent of SNe Ia explode soon after their stellar birth at the delay time of $t \sim 0.1$ Gyr, while the remaining 50 percent have a much wider distribution of the delay time around $t \sim 3$ Gyr. If the delay time distribution (DTD) of SNe Ia is observationally obtained, we are able to preclude some models that are inconsistent with the DTD.

Recently, the direct measurement of the DTD has been reported by Totani et al. (2008). Their DTD shows a featureless power law ($\propto t^{-n}$, $n \approx 1$) between $t \sim 0.1$ and $\sim 10$ Gyr. On the basis of their results, they argued that the DTD strongly supports the DD scenario of SN Ia progenitors mainly because the featureless power law distribution is in good agreement with the prediction of the DD scenario. They also concluded that the SD scenario is not well supported mainly because some “detailed” binary population synthesis codes predict prominent peaks in the DTD at characteristic time scales (e.g., Belczynski et al. 2005; Meng et al. 2008; Ruiz-Lapuente & Canal 1998; Yungelson &Livio 2000), although some “simple” SD models with simplified treatments of binary evolution have broad DTD shapes similar to the observed DTD (e.g., Greggio 2005; Matteucci et al. 2006; Kobayashi & Nomoto 2008).

In the SD scenario, the DTD is closely related to the main-sequence (MS) lifetime of the companion star and thus the initial mass of the companion (secondary), $M_{2,0}$. This is because the mass transfer from the companion to
the critical mass (negligibly small. the accreted mass during the common envelope phase is too close, the more massive (primary with the mass of the WD and the companion (Greggio 2005).

In the “detailed” SD models, they follow each binary evolution including many binary evolutionary processes and, as a result, the mass of the companion that can produce an SN Ia is constrained to a certain range, e.g., $M_{2,0} \approx 2 - 3.5 M_\odot$ in Meng et al. (2008). Therefore, the delay time is also constrained to a narrow range of $t \approx 0.3 - 1.2$ Gyr, which is inconsistent with the observed DTD.

In some “simple” SD models, a mass range of the companion is assumed a priori to be $M_{2,0} = 0.8 - 8 M_\odot$ simply from the condition of $M_{2,0} < M_{1,0}$ without taking into account the constraints on the mass accretion rate onto the WD and thus on the separation between the WD and the companion (Greggio 2005).

In the present paper, we show that the SD model with taking into account the “detailed” binary evolution is viable against the observed DTD. Actually, the required broad distribution of the companion mass, $M_{2,0} \sim 0.9 - 6 M_\odot$ has already been predicted by a recent “detailed” progenitor model of SNe Ia (Hachisu et al. 2008). However, Hachisu et al. did not present any DTDs mainly because at that time there were no observational data to compare with the theoretical results. Here we present DTDs on the basis of the new “detailed” SD models (Hachisu et al. 2008) in §§2 and 3 and compare with the observation (Iotani et al. 2008) in §4.

2. MASS-STRIPPING EFFECT AND BINARY EVOLUTION

We start the binary evolution from the zero-age MS. Unless the initial separation of the binary components is too close, the more massive (primary with the mass of $M_{1,0}$) component evolves to a red giant star (with a helium core) or an AGB star (with a C+O core) and fills its Roche lobe. Subsequent mass transfer from the primary to the secondary is rapid enough to form a common envelope. The binary separation shrinks greatly owing to the mass and angular momentum losses from the binary system during the first common envelope evolution. The hydrogen-rich envelope of the primary component is stripped away and the primary becomes a helium star or a C+O WD. The helium star further evolves to a C+O WD after a large part of helium is exhausted by core-helium-burning. Thus we have a binary pair of the C+O WD and the secondary star that is an MS star; the mass of the secondary star, $M_2$, is still close to $M_{2,0}$, because the accreted mass during the common envelope phase is negligibly small.

After the secondary evolves to fill its Roche lobe, the WD accretes mass from the secondary and grows to the critical mass ($M_{\text{crit}} = 1.38 M_\odot$) and explodes as an SN Ia if the initial binary orbital period ($P_0$) and the initial mass of the secondary ($M_{2,0}$) are inside the regions (labeled “initial”) shown in Figure 1. There are two separate regions; one is for binaries consisting of a white dwarf and a main-sequence star (WD + MS) and the other is binaries consisting of a white dwarf and a red giant (WD + RG). Here the metallicity and the initial white dwarf mass are assumed to be $Z = 0.02$ and $M_{\text{WD,0}} = 1.0 M_\odot$. Note that the WD with $M_{\text{WD,0}} = 1.0 M_\odot$ for $Z = 0.02$ forms from the primary star of $M_{1,0} \sim 7 M_\odot$ (Umeda et al. 1999).

Here we emphasize the effects of two important processes in the binary evolutions. The first one is the accretion wind evolution. Mass-accreting WDs blow strong winds when the mass transfer rate onto the WD exceeds the critical rate of $M_{\text{crit}} \sim 1 \times 10^{-5} M_\odot$ yr$^{-1}$ (Hachisu et al. 1996). The angular momentum taken away by this fast wind is much smaller than the orbital angular momentum, so that the separation of the binary does not shrink (Hachisu et al. 1999a). If we ignore this wind effect, almost all the binaries would undergo a common envelope phase and merge (the WD + MS systems) or form a double degenerate system (the WD + RG systems) due to a large amount of angular momentum loss. None of them becomes an SN Ia through the SD channel (e.g., Hachisu et al. 1999a).

The second one is the mass-stripping from the secondary surface by the WD winds. This attenuates the mass transfer rate from the secondary to the WD, so that the binary can avoid the formation of a common envelope even for a rather massive secondary (Hachisu et al. 1999a, 2008). In our results in Figure 1, this mass-stripping effect is critically important.

Our results showed that the “initial” region of WD + MS systems extends up to such a massive ($M_{2,0} \sim 5 - 6 M_\odot$) secondary, which consists of a very young
population of SNe Ia with such a short delay time as $t \lesssim 0.1$ Gyr. On the other hand, the WD + RG systems with a less massive RG ($M_{2,0} \sim 0.9 - 1.0 M_\odot$) consist of a very old population of SNe Ia of $t \gtrsim 10$ Gyr.

3. DELAY TIME DISTRIBUTION

The birth rate of SNe Ia in our Galaxy is expressed as

$$\nu = 0.2 \int \int \int_D \frac{dM_1}{(M_{1,0})^{2.5}} f(q) dq d \log a \text{ yr}^{-1},$$

along equation (1) of Iben & Tutukov (1984), where

$q = M_{2,0}/M_{1,0}$, $a$, and $M_{1,0}$ are the mass ratio, the separation, and the primary mass in solar mass units, respectively, at the birth of a binary and $D$ is the SN Ia region in the ($M_{1,0}, q, a$)-space. Dividing the three-dimensional space of ($M_{1,0}, q, a$) into grids of ($M_1, q_1, a_1$), we follow the binary evolution starting from the initial state of ($M_1, q_1, a_1$) and obtain $\nu$ for the binaries which finally explode as SNe Ia. At the same time, we record the delay time of $t$ for each ($M_1, q_1, a_1$). In our calculation, the SN Ia region of $D$ consists of these SN Ia grid points. This procedure can easily be done when we know the “initial” SN Ia regions for both the WD + MS and WD + RG systems as shown in Figure 4 of Hachisu et al. (1999a, 1999b) for the WD + MS system and Figure 12 of Hachisu et al. (1999a) for the WD + RG system, we have obtained such SN Ia regions for different initial WD masses, $M_{WD,0} = 0.7, 0.8, 0.9, 1.0$, and $1.1 M_\odot$, which formed from the primary star of masses $M_{1,0} \sim 4, 5, 6, 7$, and $8 M_\odot$ at the birth, respectively, for $Z = 0.02$ (Umeda et al. 1999). Using these results, we have estimated the SN Ia birth rate in our Galaxy as $\nu_{WD+MS} = 0.0035$ yr$^{-1}$ and $\nu_{WD+RG} = 0.0032$ yr$^{-1}$, respectively (see Hachisu et al. 1999a, b, 2008, for more detail). Here we assume $f(q) = 1$ along Iben & Tutukov (1984). Therefore, the relative ratio of the SNe from the WD + MS progenitors to those from the WD + RG progenitors is $r_{MS/RG} = 1.1$.

Now we estimate the DTD of SNe Ia forming from the WD + MS and WD + RG systems, by integrating
only the initial sets of \((M_i, q_j, a_k)\) having the delay time between \(t - \Delta t\) and \(t + \Delta t\), as

\[
\text{DTD}(t) \propto \frac{1}{2\Delta t} \int \int \int_{t-\Delta t}^{t+\Delta t} \frac{dM_{1,0}}{(M_{1,0})^{2.5}} f(q) \, dq \, d\log a,
\]

where we adopt \(f(q) = 1\) and 10 bins of the delay time at \(t = 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, \) and \(25.6\) Gyr. The resultant DTD as summarized in Table 1 is not normalized, thus being scale-free. We normalize our DTD by fitting the value to the observation at 11 Gyr as shown in Figure 2. Our DTD shows a featureless power law (\(\propto t^{-n}\), \(n \approx 1\)) from 0.1 to 12 Gyr, which is in good agreement with Totani et al.'s (2008) DTD and the data at 11 Gyr by Mannucci et al. (2007). Here, we assume \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\) for the Hubble constant. Thus the DTD on the basis of our "detailed" SD model of SN Ia progenitors is consistent with the observation. It should be noticed that we plotted the number ratio of SN Ia against the delay time in Figure 12 of Hachisu et al. (2008), which clearly shows a bimodality of SN Ia progenitors, but the number ratio itself is not equal to the DTD of SN Ia because the DTD is time-derivative of the number ratio.

Here, for instructive purposes, we derive an approximate power law of our DTD. The main-sequence lifetime of the secondary, \(t_2\), can be estimated as \(t_2 \propto M_{2,0}/L_{2,0} \propto (M_{2,0})^{1-m}\), where the mass-luminosity relation at the zero-age main-sequence is approximately written as \(L_{2,0} \propto (M_{2,0})^m\) with \(m = 3.5\) for \(M_{2,0} = 3 - 7\) M\(_\odot\). The appropriate range of initial separation (\(\Delta \log a\)) is roughly proportional to the range of orbital period, i.e., \(\Delta \log a \approx (2/3) \Delta \log P\), so the area of \(\Delta M_{2,0} \Delta \log a\) is calculated approximately from the SN Ia region in the log \(P - M_2\) plane for a given \(M_{1,0}\) like in Figure 4. This area becomes narrower as the initial WD mass, \(M_{\text{WD},0}\), decreases as shown in Figure 2 of Hachisu et al. (2008). The initial WD mass is closely related to the initial primary mass, \(M_{1,0}\), so that we numerically obtain the approximate relation of

\[
\int \int_D dM_{2,0} \, d\log a \propto (M_{1,0})^{2.5},
\]

for the fixed \(M_{1,0}\) between \(6 < M_{1,0} < 9\). We also numerically obtain a similar relation of

\[
\int \int_D (M_{1,0})^{-3.5} dM_{1,0} \, d\log a \propto (M_{2,0})^{-1.0},
\]

for the fixed \(M_{2,0}\) between \(3 < M_{2,0} < 6\). Then the DTD can be approximated as

\[
\text{DTD}(t) \propto \frac{1}{2\Delta t} \int \int \int_{t-\Delta t}^{t+\Delta t} \frac{dM_{1,0}}{(M_{1,0})^{2.5}} f(q) \, dq \, d\log a \\
\propto \frac{1}{2\Delta t} \int \int \int_{t-\Delta t}^{t+\Delta t} \frac{dM_{2,0}}{M_{2,0}} \propto \frac{1}{2\Delta t} \int \int \int_{t-\Delta t}^{t+\Delta t} \frac{dt}{t_2} \propto t^{-7/5},
\]

for \(\Delta t \ll t_2\). Here, we assume \(f(q) = 1\) and \(M_{2,0} \propto (t_2)^{-1/2.5}\). Strictly speaking, the power of \(M_{2,0}\) in equation (3) is somewhat between \(-1.0\) and \(-0.5\). If we adopt the power of \(-0.5\), the final power of the delay time, \(t\), in equation (5) changes from \(-1.0\) to \(-1.2\).

For the WD + RG system, we use \(m = 5\) for the mass-luminosity relation of the zero-age main-sequence stars with \(M_2 = 0.7 - 2\ M_\odot\) and \(M_{2,0} \propto (t_2)^{-1/4}\). Applying the area of the SN Ia regions that have been already calculated as shown in Figure 12 of Hachisu et al. (1999a), we numerically obtain the same approximate relation as given by equation (3) for \(7 < M_{1,0} < 9\) and equation (4) for \(0.9 < M_{2,0} < 2\). Then we have the same power law index as in equation (5), i.e., DTD\((t) \propto t^{-1}\) for the WD + RG channel.

In both the WD + MS and WD + RG channels, the DTD has the power law index (\(\propto t^{-n}\)) close to \(n = 1\) regardless of the mass-lifetime dependence of \(M_{2,0} \propto (t_2)^{-1/2.5}\) for the WD + MS or \(M_{2,0} \propto (t_2)^{-1/4}\) for the WD + RG system. The important “details” to realize such DTDs is how the SN Ia region shrinks or expands as the initial secondary mass, \(M_{2,0}\), decreases. Here, the approximate relation given by equation (3) holds for both the WD + MS and WD + RG systems, which leads to the logarithmic form of the DTD\((t) \propto \int d\log M_{2,0}/\Delta t \propto \int d\log t_2/\Delta t \propto t^{-1}\) regardless of the mass-lifetime dependence, as seen in equation (5).

4. CONCLUSIONS AND DISCUSSION

Totani et al. (2008) argued that the “detailed” SD models on the basis of the population synthesis should have prominent peaks in the DTD at characteristic time scales of the secondary mass, thus being inconsistent with the observation. As already shown in Figure 2, however, our DTD on the basis of the “detailed” binary evolution models has a featureless power law, being in good agreement with the observation. This is because the mass of the secondary star of the SN Ia system ranges from \(M_{2,0} \sim 0.9\) to \(6\) M\(_\odot\) (Fig. 1) due to the effects of the WD winds and the mass stripping. In our model, moreover, the number ratio of SN Ia between the WD + MS component and the WD + RG component is \(r_{\text{MS}/\text{RG}} = 1.1\). Such almost equal contributions of the two components help to yield a featureless power law as discussed below.

As for the metallicity effect (e.g., Kobayashi & Nomoto 2008), we assume that the metallicity had already increased to \(Z = 0.02\) (or more) at the birth of progenitor stars mainly because the galaxies studied by Totani et al. (2008) consist of old galaxies, the metallicity of which had already increased to \(Z = 0.02\) or more. Therefore, Totani et al.’s (2008) data should not show any metallicity effect even if the metallicity effect really exists.

In order to see the effect of different initial distributions of the binary mass ratio \(q\) (e.g., Greggio & Renzini 1983; Greggio 2003; Kobayashi & Nomoto 2008, Figure 2), shows that the DTD for \(f(q) = 2/(1+q)^2\) is in good agreement with the observation. The other DTD for \(f(q) = 24q^2/(1+q)^4\) shown in Figure 2 is marginally consistent with the observation.

Such a weak dependence stems from the fact that the ratio of the two SN Ia components, \(r_{\text{MS}/\text{RG}}\), depends slightly on \(f(q)\). The WD + MS component has a relatively short delay time, and tends to have a large \(M_{2,0}\). In contrast, the WD + RG component has a long delay time, having a small \(M_{2,0}\). In Figure 1 for example, \(M_{1,0} \sim 7\ M_\odot\) for \(M_{\text{WD},0} \sim 1\ M_\odot\), while \(M_{2,0} \sim 0.9 - 3\ M_\odot\) for the WD + RG system, i.e., \(q \sim 0.13 - 0.4\). The q distribution of \(f(q) = 24q^2/(1+q)^4\)
TABLE 1

| delay time (Gyr) | WD + MS$^b$ | WD + RG$^c$ | total |
|------------------|-------------|-------------|-------|
| 0.05             | 0.0         | 0.0         | 0.0   |
| 0.1              | 3.85        | 0.0         | 3.85  |
| 0.2              | 1.56        | 0.0         | 1.56  |
| 0.4              | 0.617       | 0.0227      | 0.640 |
| 0.8              | 0.172       | 0.177       | 0.349 |
| 1.6              | 0.0         | 0.189       | 0.189 |
| 3.2              | 0.0         | 0.0734      | 0.0734|
| 6.4              | 0.0         | 0.0286      | 0.0286|
| 12.8             | 0.0         | 0.00913     | 0.00913|
| 25.6             | 0.0         | 0.000417    | 0.000417|

$^a$ binary mass ratio distribution of $f(q) = 1$, IMF of $\alpha = 2.5$, and metallicity of $Z = 0.02$. $^b$ $\nu_{\text{WD+MS}} = 0.0035$ yr$^{-1}$ in our Galaxy. $^c$ $\nu_{\text{WD+RG}} = 0.0032$ yr$^{-1}$ in our Galaxy.

has a peak at $q = 1$ and takes smaller values at smaller $q$. As a result, $r_{\text{MS/RG}} = 1.4$ for this $f(q) = 24q^2/(1+q)^2$ is slightly larger than $r_{\text{MS/RG}} = 1.0$ for $f(q) = 2/(1+q)^2$. Thus the DTDs of our “detailed” SD models is not so sensitive to the mass ratio distribution $f(q)$, suggesting that almost a featureless power law shape ($\propto t^{-1}$, $n \approx 1$) from $t \sim 0.1$ to 10 Gyr is common among our “detailed” SD models as long as the mass range of the secondary is $M_{2,0} \sim 0.9 - 6 M_\odot$.

We also calculate a DTD with a different power law index of IMF, i.e., $\alpha = 2.35$ instead of $\alpha = 2.5$ in equations (1) and (2). As shown in Figure 21, the results are hardly affected by changing $\alpha$ of the IMF as long as $\alpha = 2.35 \pm 0.15$.

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