Delay Time Distribution Measurement of Type Ia Supernovae by the Subaru/XMM-Newton Deep Survey and Implications for the Progenitor

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Abstract

The delay time distribution (DTD) of type Ia supernovae (SNe Ia) from star formation is an important clue to reveal the still unknown progenitor system of SNe Ia. Here we report on a measurement of the SN Ia DTD in a delay time range of \( t_{\text{Ia}} = 0.1 \sim 8.0 \) Gyr by using the faint variable objects detected in the Subaru/XMM-Newton Deep Survey (SXDS) down to \( i' \sim 25.5 \). We select 65 SN candidates showing significant spatial offset from nuclei of the host galaxies having old stellar population at \( z \sim 0.4 \sim 1.2 \), out of more than 1,000 SXDS variable objects. Although spectroscopic type classification is not available for these, we quantitatively demonstrate that more than \( \sim 80 \% \) of these should be SNe Ia. The DTD is derived using the stellar age estimates of the old galaxies based on 9 band photometries from optical to mid-infrared wavelength. Combined with the observed SN Ia rate in elliptical galaxies at the local universe, the DTD in \( t_{\text{Ia}} \sim 0.1 \sim 10 \) Gyr is well described by a featureless power-law as \( f_D(t_{\text{Ia}}) \times t_{\text{Ia}}^{\alpha} \) with \( \alpha \sim -1 \). The derived DTD is in excellent agreement with the generic prediction of the double-degenerate scenario, giving a strong support to this scenario. In the single-degenerate (SD) scenario, although predictions by simple analytic formulations have broad DTD shapes that are similar to the observation, DTD shapes calculated by more detailed binary population synthesis tend to have strong peaks at characteristic time scales, which do not fit the observation. This result thus indicates either that the SD channel is not the major contributor to SNe Ia in old stellar population, or that improvement of binary population synthesis theory is required. Various sources of systematic uncertainties are examined and tested, but our main conclusions are not affected significantly.

Key words: stars: supernovae: general — galaxies: evolution — cosmology: observations

1. Introduction

It is widely believed that type Ia supernovae (SNe Ia) are thermonuclear explosions of carbon-oxygen white dwarfs in binary systems, triggered when a white dwarf grows up to the Chandrasekhar mass by accretion from its companion (see Nomoto et al. 1997; Hillebrandt & Niemeyer 2000; Livio 2001 for reviews). However, the progenitor binary system leading to SNe Ia is still unknown, and there are two competing scenarios for the accretion process triggering SNe Ia. In the single-degenerate (SD) scenario, the accretion is from a non-degenerate companion star (Whelan & Iben 1973; Nomoto 1982), while in the double-degenerate (DD) scenario, a merger of two white dwarfs results in a SN Ia (Iben & Tutukov 1984; Webbink 1984). To reveal the progenitor is important not only for better understanding of this one of the brightest explosions in the universe, but also for controlling systematic uncertainties when SNe Ia are used as a standard candle to measure the expansion rate of the universe (Riess et al. 1998; Perlmutter et al. 1999). SNe Ia are expected to have a wide range of delay time from star formation to supernova explosions, and the delay time distribution (DTD) can be used to discriminate the proposed progenitor models, since different progenitor scenarios predict different DTDs. The DTD \( f_D(t_{\text{Ia}}) \) is equivalent to the SN Ia occurrence rate as a function of the Ia delay time \( t_{\text{Ia}} \), for a single-burst stellar population of a unit stellar mass. Hence, observational studies on SN Ia rates should be able to constrain DTD (Mannucci et al. 2006 and references therein). One such approach is to examine the evolution of the cosmic SN Ia rate density (Pain et al. 2002; Gal-Yam & Maoz 2004; Maoz & Gal-Yam 2004; Strolger et al. 2004; Dahlén et al. 2004; Barris & Tonry 2006; Förster et al. 2006; Neill et al. 2006; Botticella et al. 2008; Oda et al. 2008; Blanc & Greggio 2008). However, there is a degeneracy between SN Ia DTD and the cosmic star formation history, and it is difficult to derive a strong constraint on DTD from the currently available data (Förster et al. 2006; Botticella et al. 2008; Oda et al. 2008; Blanc & Greggio 2008). Another approach is to study the dependence of SN rate on the host galaxy properties, such as colors or spectral energy distribution (SED) (Mannucci et al. 2005; Scannapieco & Bildsten 2005; Sullivan et al. 2006; Aubourg et al. 2007). This approach has al-
ready given some useful constraints on DTD, indicating the existence of SN Ia populations having both short (\(\lesssim 0.1\) Gyr) and long (\(\gtrsim 10\) Gyr) delay times. However, the functional shape of \(f_D(t_{\text{delay}})\) has not yet quantitatively been constrained well. What has been done in previous studies is to assume simple mathematical functions for DTD or adopt theoretical DTD models to predict the distributions of some observational quantities such as host galaxy colors, and then compare them to the observed data. A clear next step is a measurement of DTD, i.e., to constrain the functional form of DTD directly from the observed data, rather than testing particular DTD functions or models.

For a DTD measurement, one needs to reliably estimate the delay time of an observed SN Ia and the stellar mass of its host galaxy. The mean stellar age of the host galaxy is an indicator of the delay time, but it is unreliable when the stellar age distribution has a large dispersion, as in galaxies having extended star formation history. The ideal population for this purpose is old galaxies with an approximately uniform stellar age, which experienced major star formation episode in the past and have little or no star formation activity at the time of a SN explosion. Present-day elliptical galaxies are good examples, but they have a typical age of \(\gtrsim 10\) Gyr (Barber et al. 2007; Jimenez et al. 2007), and hence we need to observe SNe at higher redshifts to get a sample of SNe having shorter delay times. However, both detection of SNe and stellar age estimate of host galaxies become difficult at high redshifts.

The Subaru/XMM-Newton Deep Survey (SXDS, Furusawa et al. 2008), which is the deepest survey among those wider than \(\sim 1\) deg\(^2\) with a broad coverage of various wavelengths, provides a unique data set for this purpose. In optical bands, this field has been observed repeatedly with some time intervals, and a systematic variable object search has been performed (Morokuma et al. 2008a, b), leading to detection of more than 1,000 variable objects down to a limiting variability magnitude of \(m_v \sim 25.5\) (AB). The majority of them are high-redshift supernovae and active galactic nuclei (AGNs). This data set includes many passively evolving old galaxies at redshift \(z \sim 1\), which are believed to be the direct ancestors of the present-day elliptical galaxies (Yamada et al. 2005).

We can estimate the stellar age and stellar mass of host galaxies by photometric redshift calculations using the rich photometric data in the 9 band filters (\(BVR_{i}^{i}\)z'JK, 3.6, and 4.5\(\mu\)m). The required accuracy for the age estimate in this work is about a factor of two, and we will show that such an accuracy can be achieved for the galaxies used in this work, by a variety of tests for the age estimates.

In this paper we measure the SN Ia DTD by selecting the SXDS variable objects found in old or passively evolving galaxies at \(z \sim 0.4–1.2\). Spectroscopic SN type confirmation is not available for the faint SXDS SN candidates. It is difficult to construct a complete high-redshift SN sample with spectroscopic type classification under homogeneous conditions of spectroscopic observation, and contamination of SNe with no or poor spectroscopic data is one of the most challenging sources of uncertainty in SN rate studies (Strolger et al. 2004; Neill et al. 2006; Sullivan et al. 2006; Poznanski et al. 2007). Here, instead of using spectroscopic information, we select variable objects in old galaxies with spatial offset from the galactic centers, and hence the majority of them are expected to be SNe Ia. In fact, we will quantitatively demonstrate that more than 80% of them should be SNe Ia, based on the properties of the SN candidates and their host galaxies.

It should be noted that selecting SNe only in a particular type of galaxies does not induce bias in the DTD estimates, since we measure SN Ia rate normalized by stellar mass of host galaxies having the same type. This is in contrast to measurements of total cosmic SN rate density, in which selection of any particular galaxy type obviously leads to an underestimate of the total rate. On the other hand, we cannot measure DTD at short delay times obviously because of selecting old galaxies. We will present a measurement of DTD in a range of \(t_{\text{delay}} = 0.1–8.0\) Gyr, corresponding to the distribution of mean stellar ages of the old galaxies used in this work. Our DTD measurement will be supplemented by the SN Ia rate measured for elliptical galaxies in the local universe, to obtain DTD in \(t_{\text{delay}} \sim 0.1–10\) Gyr. The derived DTD will then be compared with a wide range of the existing theoretical DTD predictions, to get implications for the SN Ia progenitor.

In section 2, we describe the SXDS data set and selection procedures of old galaxies and SN candidates. In section 3, we describe the formulations of DTD measurement and present the results. In section 4, we examine various systematic uncertainties in our DTD estimates. We then discuss about the implications for the SN Ia progenitor, from the comparison between the measured DTD and theoretical predictions (section 5). Summary and conclusions are given in section 6 with some discussions.

Throughout this paper we use the standard ΛCDM cosmological parameters of \((h, \Omega_M, \Omega_{\Lambda}) = (0.7, 0.27, 0.73)\), where \(h \equiv H_0/(100\text{ km/s/Mpc})\), and magnitudes are given in the AB magnitude system unless otherwise stated.

2. The SXDS SN Ia Candidates

2.1. the SXDS Data and Photometric Redshift Calculations

We utilize the rich photometric data set of SXDS in \(BV_{\text{R}_{i}}^{i}, i'z'\) bands obtained by the Subaru/Suprime-Cam (Furusawa et al. 2008), in \(JK\) bands obtained by the UKIDSS survey (Warren et al. 2007), and in 3.6 and 4.5\(\mu\)m bands obtained by the SWIRE survey (Lonsdale et al. 2004), with the limiting magnitudes (3σ) of 28.4, 27.8, 27.7, 27.7, 26.6, 24.1, 24.0, 23.1, and 22.4, respectively, for aperture diameters of 2 (optical and \(JK\)) and 3.8 (the Spitzer bands) arcsec. The point-spread-function size of the optical images is about 0.8 arcsec FWHM (1 pixel = 0.2 arcsec). The total survey area used in the variable object survey (Morokuma et al. 2008a) is 0.918 deg\(^2\). Though the \(JK\) data is available only for 64.5% of the SXDS field, almost all (97.5%) of the SXDS field is covered by the Spitzer data. This is important for reliable stellar mass estimate, which is crucial for a study of SN Ia DTD.
Fig. 1. The properties of the old galaxies selected for the SN search. Upper left panel: the $i'$-band magnitude distributions of all the 16,492 old galaxies used in the analysis (solid), the 314 old galaxies with spectroscopic data (dotted), and the host galaxies of the 65 SN candidates (dashed). The dot-dashed line is the distribution of the $i'$-band variability magnitude of the 65 SN candidates. Upper right panel: the $A_V$ distributions of the old galaxies (solid), non-old galaxies (dashed), and all (old plus non-old) galaxies (dot-dashed) with $m_{i'} \leq 24.0$ and $m_{3.6} \mu M_{\odot} \leq 22.8$. Middle and lower panels: the distributions of $\langle t_\ast \rangle$, $t_{ga}/\tau_{SF}$, redshift, and stellar mass of all the old galaxies (solid) and the host galaxies of the SN candidates (dashed).
Therefore we select relatively bright 45,374 galaxies with $m_{i' } \leq 24.0$ and $m_{3.6\mu m} \leq 22.8$, for reliable photo-z and stellar mass/age estimations. Stars have been removed by the two-color plot $(m_{R_0} - m_{i'}$ versus $m_{R_0} - m_{3.6\mu m})$ as in Morokuma et al. (2008a).

Photometric redshift ($z_{\text{ph}}$) calculations are performed by using the publicly available code hyperz (Bolzonella, Miralles, & Pell 2000), with the GALAXEV library (Bruzual & Charlot 2003) of stellar population synthesis models based on the Padova 1994 evolutionary tracks. In our baseline analysis, we use the library assuming the Salpeter initial mass function (IMF) in the mass range of 0.1–100 $M_\odot$ and a supersolar abundance of $Z = 0.05$, since massive galaxies with old stellar population are expected to have high metallicity as known for the local elliptical galaxies (Barber et al. 2007; Jimenez et al. 2007). We use 7 models of star formation (SF) history having exponentially decaying star formation rate (SFR) with the exponential time scales of $z_{\text{ph}} = 0.1$, 0.3, 0.7, 1, 3, 5, and 15 Gyr. We also add a model with a constant SFR, and hence 8 SF history templates are used in total. Attenuation of galaxy spectra by dust is taken into account with the Calzetti law (Calzetti et al. 2000) within a range of $A_V = 0$–2, where $A_V$ is the restframe visual band attenuation. The minimum photometric error is set to be $\pm0.05$ mag, to include systematic errors for bright objects having negligibly small statistical photometric errors. Then the best-fit redshift, SF history template, galaxy age, and $A_V$ are calculated for each galaxy. The age survey range is limited not to exceed the age of the universe at a given redshift.

### 2.2. Old Galaxy Selection

We select old or passively evolving galaxies by requiring $t_{\text{ph}}/\tau_{\text{SF}} > 2.3$, where $t_{\text{ph}}$ is the galaxy age estimated by the hyperz code, i.e., the time elapsed from the beginning of the template SF history. This value is chosen so that galaxies selected by this criterion have already formed more than $[1 - \exp(-2.3)] = 90\%$ of stars that the galaxies would form in all the history. We also set a constraint of $A_V \leq 1.0$ to avoid dusty objects. After selecting galaxies within $0.4 \leq z_{\text{ph}} \leq 1.2$, which is a typical redshift range expected for SNe Ia detectable in SXDS, there remain 16,492 galaxies. We call these galaxies simply “the old galaxies” in this work for convenience.

Stellar masses are calculated for each of the old galaxies from the results of the photo-z fit. In this work, we define the stellar mass of a galaxy, $M_*$, as the integration of SFR up to its age. Because dying stars return a part of their mass into interstellar medium, this is not exactly the same as the mass locked up in stars at a given age, which changes with time even in a passive evolution phase. [The difference between the two is typically $\lesssim 30\%$; see, e.g., Fig. 7 of Sullivan et al. (2006).] It should be noted that the SFR-integrated mass is more appropriate for our purpose, because DTD should be normalized by the amount of star formation for a single starburst stellar population, which is constant against age. However, stellar mass estimations for observed galaxies are generally model-dependent. Therefore, when we derive DTD, we convert the stellar mass of our definition into $L_{K,0}$, which is the restframe $K$ band luminosity at the age of 11 Gyr (a typical age of local elliptical galaxies; see e.g., Baber et al. 2007; Jimenez et al. 2007) after passive evolution, since restframe $K$ band luminosity at a fixed large age is a good indicator of stellar mass. Then DTD will be given per unit $L_{K,0}$, and hence the difference in mass definition does not affect our DTD measurements. By this normalization, we can avoid some observational uncertainties in stellar mass estimates such as IMF (see also section 4.3), and a comparison between our results and other SN rate studies also becomes easier.

The distributions of $i'$ magnitude, $A_V$, mass-weighted mean stellar age $\langle t_* \rangle$, $t_{\text{ph}}/\tau_{\text{SF}}$, redshift, and stellar mass of these old galaxies are shown in Fig. 1. As expected for old galaxies, the distribution of $A_V$ is peaked at $A_V = 0$, with a mean value of $\langle A_V \rangle = 0.31$. The concentration to small $A_V$ values is obvious when it is compared with the distribution of the non-old galaxies. To test the reliability of photo-z, we compare the results with the spectroscopic redshifts ($z_{\text{sp}}$) of the 314 old galaxies having observed spectra in Fig. 2. The agreement is within $\pm20\%$ for the majority of the old galaxies. As a measure of deviation that is not sensitive to outliers, we computed the median of $1.48|\Delta z|/(1+z)$, which is the same as the standard deviation of $\Delta z/(1+z)$ in the case of the Gaussian distribution. The result is 0.035, and this is comparable with other photometric redshift studies at similar redshifts (e.g., Ilbert et al. 2006). The magnitude distribution of the spectroscopic sample peaks at $m_{i'} \sim 22$–23 and extends down to $m_{i'} \sim 24$ (Fig. 1), and hence our photometric old galaxy sample is restricted to the magnitude range where the spectroscopic calibration is possible. In the DTD analysis below, we use spectroscopic redshifts when available, and otherwise use photometric redshifts.

For visual demonstrations, we randomly selected 8 objects as examples from our final sample of SN candidates. The properties of the 8 objects are summarized in Table 1. The host galaxy images and the SED fits of the 8 objects are shown in Figs. 3 and 4, respectively. The photometric errors are very small especially in the optical bands since we selected bright objects, but still the agreement between the template SEDs and the observed data is quite good, which is an encouraging result about the reliability of age and stellar mass estimates.

### 2.3. Selection of the SN Candidates

We now search for variable objects associated with these old galaxies. There are 1,040 variable objects selected by $i'$ band variability in the catalog of Morokuma et al. (2008a). The SXDS field was monitored 8–10 times during about four years, with a typical time interval from a few days to one month within a year. The variable sources are selected if it is detected in the subtracted images of any possible pair of two different epochs. The detection efficiency of variable sources has been carefully determined by simulations. “The variability flux” of a SN candidate in this work refers to the maximum of differential fluxes mea-
We select variable objects within the detection isophote (i.e., the area where the surface brightness is higher than the threshold level of the source detection) of the old galaxies, and showing significant offsets ($\geq 1.9$ pixel = 0.38") from the nuclei of galaxies. The mean area of detection isophote of the old galaxies is 409 pixels. Here, the nuclei of galaxies are simply defined by their surface brightness peaks. According to the simulations using artificial objects (Morokuma et al. 2008a), this is a conservative limit to remove variable objects at nuclei of the host galaxies, i.e., AGNs. Morokuma et al. classified the nuclear variable sources into SNe or AGNs based on the light-curve shape, and they found that such classifications are broadly consistent with the X-ray information. However, the classification is rather uncertain especially for the faintest variable objects near the detection limit. Therefore we conservatively reject all nuclear variable sources. We do not use the X-ray information in the process of SN candidate selection, since a small part ($\sim 10\%$) of the survey area is not covered by the X-ray observation. Galaxies detected in the X-ray band are only 2% out of the 14,909 old galaxies observed in X-ray, which is a negligible fraction in our analysis. In fact, we confirmed that no object is detected in X-ray in our final SN candidate sample.

We thus found 67 variable objects associated with the old galaxies. We examined the optical variability information of these objects by using the full Suprime-Cam data set of the SXDS. We found that, as expected, most of them are consistent with SN-like variability. Only 2 objects show clearly AGN-like variability, i.e., flaring up more than twice during the four year observation duration. These two are removed, leaving the 65 SN candidates. Such a contamination of AGNs is possible by a chance superposition of a normal galaxy and an unrelated AGN along the line of sight (e.g., the case of an AGN initially classified as SN 1999de, Gal-Yam et al. 2008). We found that two such events are reasonable from the number of AGNs in SXDS and the area covered by the old galaxies selected here (2.3% of the total survey area).

We cannot exclude a possibility that a few more chance-superposition AGNs having SN-like light curves might be included in the 65 SN candidates. To check this, we examine the offset distribution of these objects with respect to the surface brightness profile of galaxies as follows.

2.4. Radial Distribution of the SN Candidates in Host Galaxies

We performed ellipsoidal fits for each galaxy with the Sérsic type radial profile (Sérsic 1968). The effective radius along the major and minor axes, and the Sérsic index are thus derived, taking into account the seeing. We then calculated the fraction, $f_i$, of $i'$-band light enclosed within the ellipsoidal radius to a variable object, compared with the total flux within the detection isophote (i.e., isophotal flux). Here, the nuclear region within the offset threshold (1.9 pixel radius) is excluded in the $f_i$ calculation. If we are selecting SNe Ia physically associated with the galaxies, we expect that the distribution of $f_i$ is roughly uniform between 0–1, since SNe Ia are expected to trace the host galactic light approximately (Kelly et al. 2007; Förster & Schawinski 2008). The distributions of the offsets from nuclei and $f_i$ are shown for the 65 SN candidates in Fig. 5, and in fact we find an almost uniform distribution for $f_i$.

There is a deficit at $f_i > 0.8$, and it indicates that our profile fitting is not perfect or supernova locations do not exactly trace galactic $i'$-band light. However, it is clear that the SN candidates trace the galactic light reasonably well, and hence the majority of these must be SNe physically associated with host galaxies, rather than the chance superpositions of background AGNs. It should be noted that, if there is a significant contamination of AGN chance superpositions, we expect a distribution biased to larger values of $f_i$, which is opposite from the observed trend. We thus define these 65 objects as the final SN candidate sample, and the distributions of variability and host galaxy magnitudes are shown in Fig. 1. The images of the randomly selected eight examples are shown in Fig. 3.

In the final SN sample, 7 SN candidates have measured spectroscopic redshifts of host galaxies. We confirmed that the difference between $z_{\text{spec}}$ and $z_{\text{ph}}$ is within $\sim 20\%$ for all of these, as expected from Fig. 2. The fraction of available spectroscopic redshifts, 7/65, is considerably higher than 314/16492 for the old galaxies. This is mainly because the host galaxies of the SN candidates are systematically brighter than the typical old galaxies (see Fig. 1), reflecting the fact that SN rate is roughly proportional to host galaxy luminosities. Another possible reason is that some variable objects were followed up by spectroscopic observations as a part of the Supernova Cosmology Project in collaboration with the SXDS project.
Table 1. Properties of the eight examples randomly selected from the final 65 SN sample. The redshifts are spectroscopic when available (objects 2 and 4), and otherwise photometric. Magnitudes of host galaxies and SN variability are in $i'$ band, and galaxy age ($t_{ga}$), the exponential decay time scale of SFR ($\tau_{SF}$), and mass-weighted mean stellar age ($\langle t_* \rangle$) are all in Gyr.

| Obj. No. | redshift $z$ | host mag. $M_B$ | var. mag. $M_{i'}$ | $t_{ga}$ | $\tau_{SF}$ | $\langle t_* \rangle$ | $A_V$ |
|---------|--------------|----------------|-------------------|---------|-------------|----------------|-----|
| 1       | 0.47         | 22.5           | 25.4              | 2.30    | 1.0         | 1.36           | 0.2 |
| 2       | 0.63         | 21.6           | 24.6              | 0.36    | 0.1         | 0.27           | 0.0 |
| 3       | 0.81         | 23.0           | 25.8              | 0.72    | 0.1         | 0.62           | 0.8 |
| 4       | 0.92         | 22.6           | 24.2              | 1.02    | 0.3         | 0.75           | 0.0 |
| 5       | 1.01         | 23.7           | 24.5              | 0.72    | 0.1         | 0.62           | 0.2 |
| 6       | 0.60         | 22.0           | 23.5              | 3.50    | 0.7         | 2.82           | 0.6 |
| 7       | 0.70         | 23.0           | 25.2              | 0.72    | 0.3         | 0.49           | 0.0 |
| 8       | 0.47         | 21.3           | 25.1              | 1.02    | 0.3         | 0.75           | 0.0 |

Fig. 3. The images of the eight examples randomly selected from the final SN candidates. The left panels are the 3-color composite images of the host galaxies using $BVi'$ bands. The middle panels are color contours of the host galaxy $i'$ band flux at the time of the maximum luminosity of the SN candidates, and the right panels are those of subtracted images showing the variability of the SN candidates. All panels are centered at the surface brightness peak of the host galaxies, and the locations of the SN candidates are indicated by white crosses. The properties of the eight objects are summarized in Table 1.
Fig. 4. The results of the SED fits for the old galaxies by the photometric redshift calculations, for the 8 example objects listed in Table 1. The SED is given by energy flux per unit wavelength in arbitrary units. The open squares are the observed flux. The horizontal error bars indicate the approximate width of band filters, and the vertical error bars are 1σ flux errors (difficult to see in optical bands). The flux errors include only statistical errors, while the minimum error is set to be ±0.05 mag in the photometric redshift calculations to take into account the systematic errors.
satisfying observed SN candidates associated with the old galaxies N and CC SNe, respectively, and solving the following equation: 

$$t_{\text{Ia}} \text{exp} = \bar{\langle t \rangle} - \langle \Delta t_{\text{off},i} \rangle$$

Therefore the first rough estimate of the mean DTD function is universal for all stellar populations, as often assumed in studies on the SN Ia DTD. It is possible that DTD is universal for all stellar populations, as often as-

3. Measurement of Delay Time Distribution

3.1. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that contamination of CC SNe. We implicitly assume that 

3.2. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that 

3.3. Measurement of Delay Time Distribution

3.4. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that 

3.5. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that 

3.6. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that 

3.7. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that 

3.8. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that 

3.9. The Basic Formulations

Now we estimate the DTD from the 65 SN candidates. Later (section 4) we will demonstrate that the majority of them must be SNe Ia rather than core-collapse (CC) SNe, but here we first estimate the DTD, taking into account the contamination of CC SNe. We implicitly assume that.
numbers in each
tis reasonable since CC SNe are expected to occur in star
This value is larger than that assumed for SNe Ia, but it
nearby galaxies (Oda et al. 2008 and references therein).
CC SNe, which is a typical value for CC SNe found in
project detection in SXDS (Morokuma et al. 2008a) are also
taken into account to calculate \( P_{\text{det}} \). The calculated vis-
ibility time is shown in Fig. 6. Note that this visibility
time includes the multiplicity of many SXDS observations
during four years, and not for a single epoch observation.

The expected number of CC SNe, \( N_{CC, \text{exp}} \), can be cal-
culated as

\[
N_{CC, \text{exp}} = \sum_i f_{\text{tot},i} \psi_i f_{CC} \frac{T_{V,CC}(z_i)}{(1 + z_i)},
\]

where \( \psi \) is SFR (mass per unit time) of a galaxy, and \( f_{CC} \) the production efficiency of CC SNe per unit mass of
star formation. The SFR \( \psi \) is estimated by the ob-
erved \( B \) band flux corresponding to the restframe UV
luminosity, with the conversion factor calculated by the
stellar population synthesis model used in this work. The factor \( f_{CC} \) is calculated by assuming that all stars heav-
er than 8 \( M_\odot \) produce CC SNe with the assumed IMF.
The visibility time \( T_{V,CC} \) is calculated with a standard
mixture of light curves of various types of CC SNe, as in
Oda & Totani (2005). We assume \( E(B-V) = 0.15 \) for
CC SNe, which is a typical value for CC SNe found in
nearby galaxies (Oda et al. 2008 and references therein).
This value is larger than that assumed for SNe Ia, but it
is reasonable since CC SNe are expected to occur in star
forming regions where dust abundance is generally high.
Since we selected old galaxies, we found \( N_{CC,\text{exp}} = 11.4 \)
(in all the considered range of \( t_{\text{IA}} = 0.1-8 \) Gyr) and this
is small compared with \( N_{\text{obs}} = 65 \). (See also Table 2 for
numbers in each \( t_{\text{IA}} \) bin.)

The DTD estimated by this simple formulation is shown
by open squares in Fig. 7. The error bars are statistical \( 1\sigma 
errors, which are calculated by the confidence limits of the
small number Poisson statistics (Gehrels 1986). As men-
tioned in section 2.2, the normalization by stellar mass
has been converted into that by the \( K \)-band luminosity
\( L_{K,0} \), i.e., the luminosity at the age of 11 Gyr after pas-
sive evolution. The conversion is performed by calculat-
ing \( M_*/L_{K,0} \) from the SED templates used in the photo-
z calculations. For the template of \( \tau_{\text{SF}} = 0.1 \) Gyr, we find
\( M_*/L_{K,0} = 1.8 \ [M_\odot/L_{K,0}] \). Here, we used \( (V-K)_\odot = +1.49 \) (Cox 2000) and \( f_\lambda = 4.17 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \)
for \( K = 0 \) (Zombeck 2007) in the Vega magnitude system.
We assume that the stellar age of nearby elliptical galax-
ies is 11 Gyr, based on the estimates for the SDSS early
type galaxies (Barber et al. 2007; Jimenez et al. 2007, and
see section 4.5 for more details). Hence, the observed SN
Ia rate per unit \( K \) luminosity in nearby elliptical galaxies,
\( 0.035^{+0.013}_{-0.011}(h/0.75)^2 \text{ century}^{-1} (10^{10} L_{K,0})^{-1} \) (Mannucci et al. 2005), gives an estimate of \( f_D(t_{\text{IA}}) \), which can
directly be compared with our estimates. This value is
based on the rate measurement of Cappellaro et al. (1999)
assuming \( H_0 = 75 \text{ km/s/Mpc} \), and it is translated into a
value for \( h = 0.7 \) used in this work.
Though these DTD results are derived by simply as-
suming \( t_{\text{IA}} = \langle t_\ast \rangle \), they are not significantly different from
our final results shown by the filled squares (see below),
and well described by a power-law, \( f_D(t_{\text{IA}}) \propto t_{\text{IA}}^{-\alpha} \) with
\( \alpha \sim -1 \) in 0.1–11 Gyr. However, to get a more accurate
estimate, we make a correction as follows.

### 3.2. Correction for the Delay Time Estimates

In the above formulation, we simply estimated \( t_{\text{IA}} \) of an
observed SN Ia by \( \langle t_\ast \rangle \) of its host galaxy. However, in

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**Fig. 6.** The visibility time \( T_V \) (in observer’s frame) of SNe
in SXDS as a function of redshift. The solid curve is for the
standard case of SNe Ia, while the dot-dashed curve is for CC
SNe. The dashed curves are for SNe Ia, but the luminosity is
shifted by \( \pm 0.4 \) mag. The visibility time is slightly different
in the different subfields of SXDS, and those in the SXDS-C
field (Morokuma et al. 2008a) are shown here.

**Fig. 7.** The SNe Ia DTD, \( f_D(t_{\text{IA}}) \), per unit delay time \( t_{\text{IA}} \)
[century\(^{-1}\) for a single starburst population whose total
\( K \)-band luminosity is \( 10^{10} L_{K,0} \) at the age of 11 Gyr.
The filled squares are the final observational estimates by this work
based on the baseline analysis, and the error bars are statistical
\( 1\sigma \) errors. The open squares are the same but using a
simpler method to estimate the delay time. The time bins are
the same as those for the filled squares, but the open squares
are shifted in time by \( -0.03 \) dex in this plot for presenta-
tion. The open circle is DTD inferred from the SN Ia rate in
elliptical galaxies in the local universe (Mannucci et al. 2005).

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realistically, there is a probability distribution of $t_{1a}$, which is determined by the DTD and star formation history $\psi(t)$, where $t = t_{ga} - t_{1a}$ is the time elapsed from the beginning of star formation in the host galaxy. The expectation value of the Ia delay time, $\langle t_{1a} \rangle$, is exactly the same as $\langle t_s \rangle$ only when $f_0(t_{1a})$ is constant against $t_{1a}$. The expectation value is generally given by:

$$
\langle t_{1a} \rangle = \frac{\int_{t_{1a}}^{t_{ga}} \psi(t_{ga} - t_{1a}) f_D(t_{1a}) dt_{1a}}{\int_{t_{1a}}^{t_{ga}} \psi(t_{ga} - t_{1a}) f_D(t_{1a}) dt_{1a}}.
$$

(5)

Therefore, there is a more accurate estimate is obtained by the same formulation but with a summation over galaxies satisfying $t_1 \leq t_{1a} < t_\alpha$. However, this integration diverges when $t_{1a} \rightarrow 0$ if $\alpha \leq -1$. The possibility of a significant population of the prompt SNe Ia with $t_{1a} < 0.1$ Gyr has been discussed in recent years (Scannapieco & Bildsten 2005; Mannucci et al. 2006; Sullivan et al. 2006; Aubourg et al. 2007). Such a prompt population may also affect the estimate of the delay time. Therefore, we separate the “prompt” population (defined by $t_{1a} < t_p = 0.1$ Gyr) from the “delayed” ("tardy") population ($t_{1a} \geq t_p$). Then, the DTD of the delayed component can be estimated by a modified version of eq. (1),

$$
N_{1a,Exp} + N_{pla,Exp} + N_{CC,Exp} = N_{obs},
$$

(6)

where $N_{1a,Exp}$ is now for the delayed population and the integration of eq. (5) is from $t_{1a} = t_p$ to $t_{ga}$. The expected number of the prompt Ia, $N_{pla,Exp}$, can be calculated from SFR in a similar way to get $N_{CC,Exp}$, if the integrated DTD at $0 \leq t_{1a} \leq t_p$ is given.

An obvious difficulty in this new formulation is that we need to know the DTD itself beforehand to make a measurement of DTD, because $\langle t_{1a} \rangle$ and $N_{pla,Exp}$ depend on $f_D(t_{1a})$. In fact, this circularity problem can be solved easily: first we estimate $f_D$ with an initial guess of $f_D(t_{1a})$, and then we can iterationally repeat this process with the new estimate of $f_D(t_{1a})$. The first DTD estimate with a constant $f_D$ prior (open squares in Fig. 7) is well described by a power-law ($\propto t_{1a}^{\alpha}$) at $t_{1a} \geq t_p$, and hence we assume this form of $f_D$ for the delayed population at the later iterations. For the prompt population, we assume that $f_D$ is constant at $t_{1a} \leq t_p$ and it is continuously connected to the delayed component at $t_{1a} = t_p$, for every iteration. This is reasonable from the DTD predictions by the stellar evolution theory (section 5), and the effect of this assumption on the DTD measurement will be examined in section 4.

We get sufficiently convergent results by just a few iterations of this procedure, and they are shown by filled squares in Fig. 7 as our final results. Since we selected old galaxies, $\langle t_s \rangle$ is already a good estimate of $\langle t_{1a} \rangle$, and this is why the correction is not large. The expected number of the prompt population, $N_{pla,Exp}$, is 3.6 for the entire range of $t_{1a} = 0.1$–8 Gyr, which is just 5.5% of the 65 SN candidates. The derived DTD, as well as important quantities such as $N_{pla,Exp}$, $N_{CC,Exp}$, and $N_{obs}$, are summarized in Table 2 for the six time bins in $t_{1a} = 0.1$–8 Gyr. The best fit power-law to the measured DTD is $f_D(1 \text{Gyr}) = 0.5^{+0.1}_{-0.1} \text{century}^{-1}(10^{10}L_{K,0.0})^{-1}$ and $\alpha = -1.08^{+0.15}_{-0.15}$. Here, we included the data point at $t_{1a} = 11$ Gyr in the fit.

### 4. Examination of Systematic Uncertainties

#### 4.1. Are the SN candidates really SNe Ia?

In our statistical estimation of DTD, it is not necessary to prove that all of the SN candidates are SNe Ia. Since we have already shown that the selected variable objects are tracing the light profile of host galaxies, the majority of them must be SNe Ia or CC SNe. What we need to demonstrate is, then, that about 82% of the 65 candidates are actually SNe Ia, as inferred from the estimate of $N_{CC,Exp} = 11.4$.

We first examine the $i'$ band variability magnitude $m_{var,i'}$ of the 65 SN candidates, and compare with the brightest magnitude $m_{min,i'}$ that is possible for SNe Ia corresponding to the peak luminosity. We calculated this magnitude for each SN candidate assuming the standard type Ia light curve with the mean peak $B$ magnitude used in Oda & Totani (2005). We find that most (61/65) of the SN candidates have $m_{var,i'} > m_{min,i'}$ as expected, and all objects satisfy $m_{var,i'} > m_{min,i'} - 0.53$. The four objects with $m_{var,i'} < m_{min,i'}$ are reasonable considering the dispersion of the peak $B$ magnitude of SNe Ia ($\sim$0.4 mag). On the other hand, almost half of the SN candidates have the variability magnitudes brighter than $m_{min,i'} + 1$, and such variability cannot be explained by CC SNe, because most of them are fainter than SNe Ia by 1–2 magnitudes.

### Table 2. The DTD measurements by the baseline analysis. The DTD results are shown in [century] for a single starburst population whose total K band luminosity is $10^{10}L_{K,0}$ at an age of 11 Gyr. The errors are statistical 1σ.

The number of the old galaxies ($N_{gal}$), that of the detected SN candidates ($N_{obs}$), and the expected numbers of the prompt SNe Ia ($N_{pla,Exp}$) and CC SNe ($N_{CC,Exp}$) are shown. The last column shows the mean of $\sigma_{t_{1a}}$ of galaxies in a time bin, where $\sigma_{t_{1a}}$ is the standard deviation of the probability distribution of $t_{1a}$ in a galaxy.

| $t_{1a}$ bin [Gyr] | DTD $f_D(t_{1a})$ | $N_{gal}$ | $N_{obs}$ | $N_{pla,Exp}$ | $N_{CC,Exp}$ | (\(\sigma_{t_{1a}}\)) [Gyr] |
|-------------------|--------------------|-----------|-----------|---------------|---------------|------------------|
| 0.1–0.25          | 2.89^{+0.56}_{-1.20} | 3719  | 12        | 1.0           | 2.7           | 0.05             |
| 0.25–0.5           | 1.98^{+0.73}_{-0.30} | 3086  | 14        | 0.92          | 3.1           | 0.14             |
| 0.5–1.0            | 0.84^{+0.24}_{-0.13} | 4260  | 19        | 0.88          | 3.0           | 0.30             |
| 1.0–2.0            | 0.49^{+0.07}_{-0.12} | 4764  | 19        | 0.66          | 2.3           | 0.50             |
| 2.0–4.0            | 0.12^{+0.38}_{-0.12} | 564   | 1         | 0.051         | 0.20          | 1.2              |
| 4.0–8.0            | 0.00^{+1.08}_{-0.90} | 99    | 0         | 0.007         | 0.032         | 2.1              |
Table 3. The results of the Kolmogorov-Smirnov tests for the redshift and host galaxy stellar mass distributions of the SN candidates. The chance probabilities of getting the observed distributions are shown. (See Fig. 8 for the graphical presentations of these distributions.) The columns 2–4 show the results when all SNe are assumed to be delayed SNe Ia, prompt SNe Ia, and CC SNe, respectively. The last column shows the results when the three populations are mixed with the expected numbers (45.2, 3.6, and 11.4) in our baseline analysis.

| redshift | delayed Ia | prompt Ia | CC | mix |
|----------|------------|-----------|----|-----|
| 0.07     | 0.07       | 0.05      | 0.04 | 0.40 |
| stellar mass | 0.05 | 0.07 | 0.04 | 0.48 |

(see e.g., Oda & Totani 2005).

We already made the DTD estimates, and we can predict the expected distribution of redshifts and stellar masses of host galaxies for the SN candidates, because we can calculate the expected number of SNe Ia in each galaxy. Comparison of these expected distributions with those observed provides us with an important consistency check of our DTD estimates. Figure 8 shows such comparisons, and the predictions based on our final DTD estimates are in nice agreement with the data. In the calculation of the expected redshift and stellar mass distributions, the light curve information of SNe is included through the visibility time. Therefore, we do not expect such an agreement, if our estimate of Ia/CC ratio is wrong or there is a significant contamination from any non-SN objects. In fact, the predicted distributions are in serious contradiction with the data if we assume that all the SN candidates are CC SNe. The agreement between the expected and observed distributions are quantitatively tested by the Kolmogorov-Smirnov test, and the results are given in Table 3. Acceptable fits are obtained both for the redshift and stellar mass distributions only when we make an appropriate mix of the delayed/prompt Ia and CC SNe with the relative proportions predicted by our DTD estimates: \( N_{\exp} = 45.2 \) (delayed Ia), \( 3.6 \) (prompt Ia), and \( 11.4 \) (CC). These results then give a strong support to the reliability of our DTD estimates.

It should also be noted that we selected all variable objects associated with the old galaxies with a significant offset from the nuclei. Only 2 objects were removed by AGN-like variability, which is a negligible number compared with the final 65 candidates. Therefore, our DTD measurement gives a conservative upper limits to the true DTD, and the derived DTD would always be overestimated if there was any unknown contamination from non-SN objects.

Finally, we repeated our DTD estimates with a more stringent criteria for the old galaxies, \( t_{\sigma}/t_{\sigma_{\text{SF}}} \geq 3.0 \), to select more efficiently SNe Ia rather than CC SNe. In this case, the number of the SN candidates is reduced to \( 44 \), but now \( N_{\text{CC},\exp} = 5.4 \) and \( N_{\text{pla},\exp} = 1.6 \), and hence the expected Ia (delayed+prompt) fraction is increased to 88% from 82% in the baseline analysis. The DTD estimates and the power-law fit in this case are shown in Table 4 and Fig. 9, and the difference from the baseline results is within the statistical uncertainties. It should be noted that the number of the SN candidates in the shortest bin (0.1–0.25 Gyr) is now only 5, because the possible minimum of mean stellar age is increased to 0.22 Gyr from 0.16 Gyr in the baseline analysis. Therefore, although the DTD value in the shortest time bin shows a larger deviation from the baseline analysis than in other time bins, the statistical uncertainty is quite large.

4.2. Estimates of \( \langle t_{\text{Ia}} \rangle \) and contribution from the prompt Ia population

In our analysis, the delay time \( t_{\text{Ia}} \) of each SN candidate has been estimated simply by the expectation value of \( \langle t_{\text{Ia}} \rangle \) from the star formation history of the host galaxy. We have already shown that the difference between \( \langle t_{\text{Ia}} \rangle \) and the mean stellar age (\( t_{\star} \)) is small and does not seriously affect the final results. However, the probability distribution of \( t_{\text{Ia}} \) should have some dispersion around \( \langle t_{\text{Ia}} \rangle \), and if this dispersion is larger than the bin width of the DTD estimate, it could affect the results. The dispersion around \( \langle t_{\text{Ia}} \rangle \), \( \sigma_{t_{\text{Ia}}} = ((\langle t_{\text{Ia}}^2 \rangle - \langle t_{\text{Ia}} \rangle^2)^{1/2} \) is therefore calculated for each host galaxy in a similar way to eq. (5), and their average in a \( t_{\text{Ia}} \) bin is shown in Table 2. The dispersions are typically around half of the bin widths, and hence the binning size of our DTD estimates is appropriate.

In our baseline analysis, the amount of prompt SNe Ia is calculated by assuming a constant \( f_{\text{D}}(t_{\text{Ia}}) \) at \( t_{\text{Ia}} \leq t_{\text{p}} \), and in this case the fraction of the prompt Ia is about 20% of all SNe Ia when the DTD is integrated over a range of \( t_{\text{Ia}} = 0–11 \) Gyr. However, since we selected old galaxies, \( N_{\text{pla},\exp} = 3.6 \) is just 5.5% of our 65 SN candidates. The expected fraction of prompt SNe Ia is the largest in the shortest delay time bin (0.1–0.25 Gyr), but it is still less than 10% (1.0/12, see Table 2). Therefore, our result will not be seriously affected by changing the prompt fraction, unless we assume an extremely higher prompt Ia rate (e.g., by a factor of about 10) than that assumed in the baseline analysis. We show the results of the DTD estimate when the prompt Ia population is enhanced by a factor of 2.5 from our baseline analysis in Table 4 and Fig. 9. In this case, the prompt fraction in all SNe Ia integrated over \( t_{\text{Ia}} = 0–11 \) Gyr becomes \( \sim 50\% \), which is a typical value discussed in recent papers about prompt SNe Ia (e.g., Mannucci et al. 2006; Sullivan et al. 2006). Our DTD estimate for the delayed SNe Ia is not seriously affected.

4.3. Systematic Uncertainties in Stellar Age and Mass

The estimates of stellar mass and age of the host galaxies are crucial in our DTD estimates. Since we selected old or passively evolving galaxies in a relatively bright magnitude range of \( m_r \leq 24 \), the estimates are expected to be easier than general studies of high-\( z \) galaxies. However, these estimates may sensitively depend on e.g. the SF history, IMF, and metallicity assumed in the photometric redshift calculation. Therefore the systematic uncertainties must be carefully examined.

We test several age and mass estimations with different
The cumulative distributions of redshift and stellar mass of host galaxies for the SN candidates. The thick solid lines are the observed distributions of the 65 SN candidates. The dashed and dot-dashed curves are the expected distributions for the delayed ($t_{\text{IA}} \geq 0.1$ Gyr) and prompt ($t_{\text{IA}} < 0.1$ Gyr) components of SNe Ia, respectively, and the dotted curve is that for CC SNe. The thin solid curve is our best guess, which is the sum of the three components with the expected numbers in the baseline analysis: $N_{\text{exp}} = 45.2$ (delayed Ia), 3.6 (prompt Ia), and 11.4 (CC). The results of the Kolmogorov-Smirnov test for these distributions are given in Table 3.

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**Table 4.** Examination of systematic errors in the DTD measurements. Various DTD results are shown when the analysis method is changed from the baseline analysis. The last two columns show the best-fit power-law DTD, $f_D(t_{\text{IA}}) = f_D,1Gyr(t_{\text{IA}}/1\text{ Gyr})^\alpha$.

| Analysis | $f_D(t_{\text{IA}})$ [century$^{-1}(10^{10}L_{K,0.3})^{-1}$] in $t_{\text{IA}}$ bins [Gyr] | $f_D,1Gyr$ | $\alpha$ |
|----------|---------------------------------|-------------|-------|
| baseline | 2.89$^{+1.16}_{-1.26}$ | 0.1-0.25 | 0.12$^{+0.35}_{-0.12}$ | 0.50$^{+0.11}_{-0.13}$ | -1.08$^{+0.19}_{-0.19}$ |
| $t_{\text{IA}} = (t_*)$ | 3.12$^{+1.64}_{-1.64}$ | 0.25-0.5 | 0.12$^{+0.14}_{-0.09}$ | 0.72$^{+0.14}_{-0.17}$ | -1.09$^{+0.15}_{-0.15}$ |
| $t_{\text{SP}}/t_{\text{SP}} \geq 3.0$ | 7.18$^{+5.65}_{-5.65}$ | 0.5-1.0 | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.23$^{+0.18}_{-0.18}$ |
| prompt $\times 2.5$ | 2.32$^{+1.16}_{-1.16}$ | 1.0-2.0 | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
| solar Z | 1.64$^{+0.81}_{-0.81}$ | 2.0-4.0 | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
| Chabrier IMF | 3.00$^{+1.65}_{-1.23}$ | 4.0-8.0 | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
| K97 | 6.43$^{+2.65}_{-2.08}$ | 4.87$^{+1.44}_{-1.18}$ | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
| $A_V < 0.5$ | 3.27$^{+2.88}_{-1.97}$ | 0.87$^{+0.55}_{-0.36}$ | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
| SN +0.3 mag | 3.21$^{+1.78}_{-1.34}$ | 0.94$^{+0.34}_{-0.22}$ | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
| SN -0.3 mag | 2.58$^{+1.44}_{-1.14}$ | 0.75$^{+0.21}_{-0.13}$ | 0.11$^{+0.30}_{-0.06}$ | 0.73$^{+0.17}_{-0.17}$ | -1.05$^{+0.16}_{-0.16}$ |
prescriptions of the photometric redshift calculation as follows. We first try the two cases of changing metallicity into the solar abundance ($Z = 0.02$) and changing IMF into the Chabrier (2003) IMF, from the baseline analysis. The choice of the supersolar metallicity ($Z = 0.05$) in the baseline analysis is motivated by the metallicity estimates of local early-type galaxies (Barber et al. 2007; Jimenez et al. 2007), as mentioned in §2.1. Recent observations of the mass-metallicity relation at various redshifts give a further support to this choice. According to the mass-metallicity relation of Savaglio et al. (2005) measured for galaxies at a similar redshift range ($0.4 \leq z \leq 1.0$) to our sample, metallicity of the old galaxies selected in this work is expected to be larger than the solar value, even when our definition of the stellar mass (integration of SFR) is taken into account. Therefore our examination in the metallicity range of $Z = (1–2.5) Z_⊙$ is reasonable to check the systematic uncertainties in DTD.

Furthermore, we used a completely different population synthesis model by Kodama & Arimoto (1997, hereafter KA97), based on an independent stellar spectrum library. We used the $M_V = -21.98$ model in the metallicity-sequence KA97 models as a template. In this model, a gas infall and galactic wind are taken into account rather than a simple exponential SFR evolution, and the chemical evolution is solved in a self-consistent manner. This is a model for a local elliptical galaxy, and the star formation time scale is about $\tau_{\text{SF}} \sim 0.1$ Gyr. We have only one template for the star formation history, and hence the age estimate is likely to be less accurate than the baseline analysis, but we can check the dependence on different stellar population synthesis models as well as on the number of used SF history templates.

In Fig. 10, we show the distribution of $\langle t_\ast \rangle /\langle t_\ast \rangle_{bl}$ and $M_\ast /M_\ast_{bl}$ of the old galaxies, i.e., the ratios of $\langle t_\ast \rangle$ and $M_\ast$ estimated by different prescriptions to those in our baseline analysis. The logarithmic means and standard deviations of these quantities are tabulated in Table 5. It can be seen that the means of $\langle t_\ast \rangle$ are not significantly changed, and the typical dispersion of $\langle t_\ast \rangle /\langle t_\ast \rangle_{bl}$ is about a factor of two. This means that the bin width of our DTD measurements is not unreasonably small compared with the systematic uncertainties. As for stellar masses, systematic offsets of mean values of $M_\ast /M_{\ast, bl}$ from unity can be seen. However, for the solar $Z$ and the Chabrier IMF cases, these offsets are considerably reduced when we consider the $K$-band luminosity at the age of 11 Gyr ($L_{K,0}$) as the mass indicator. The mass-to-light ratios are $M_\ast /L_{K,0} = 2.0$ and $1.4 \, [M_\odot/L_{K,0}]$ for the solar $Z$ and the Chabrier IMF cases, respectively (1.8 for the baseline analysis), and hence the effective offsets in log$_{10} L_{K,0}$ now become 0.056 and −0.043, respectively, i.e., less than ~10% difference in DTD estimates. This demonstrates the merit of using $L_{K,0}$ as the mass indicator to reduce the uncertainties about stellar mass estimates. On the other hand, $M_\ast /L_{K,0} = 2.1 \, [M_\odot/L_{K,0}]$ for the KA97 model and it cannot compensate the large offset of $M_{\ast, bl}$. This is most likely a result of the limited SF history template.
in the estimates using the KA97 model (only 1 template corresponding to \(z_{\text{spec}} \sim 0.1\) Gyr). It is expected that the age estimates with a single small value of \(z_{\text{spec}}\) tend to be underestimate of the true age, and this trend is in fact seen in the left panel of Fig. 10. The underestimate in stellar age would result in an underestimate in the stellar mass.

To examine the sensitivity of our DTD estimates to these uncertainties of stellar ages and masses, we repeated the DTD estimates but using \(M_*\), \((M_*/L_{K,0})\), and \((t_{\text{phot}})\) calculated with the different prescriptions, and the results are shown in Table 4 and Fig. 9. The change in the DTD is within the statistical \(1\sigma\) errors of the baseline results for most of the data points. The KA97 model case shows a large deviation from the baseline analysis at \(t_{\text{phot}} < 0.5\) Gyr, compared with the other cases. This is probably due to the age underestimates by a single SF template as discussed above, and we consider that the baseline results are more reliable than those using the KA97 model. The data points at \(t_{\text{phot}} = 0.5\)–2 Gyr are quite robust against these tests.

Furthermore, we calculate \(\langle t_*\rangle_{\text{spec}}\) and \(M_*\,_{\text{spec}}\) for the old galaxies with spectroscopic redshifts, to examine the systematic uncertainties in stellar age and mass coming from the uncertainty about redshift. These are calculated from the same photometric redshift calculations, but fixing the redshift at the value known by spectroscopic observations. The results are shown in Fig. 11, as the ratios to \(\langle t_*\rangle_{\text{phot}}\) and \(M_*\,_{\text{phot}}\) obtained by the normal photometric redshift calculations (i.e., redshift treated as a free parameter). The logarithmic mean and the standard deviation of these ratios are shown in Table 5. Many galaxies have exactly the same value of \(\langle t_*\rangle_{\text{spec}} = \langle t_*\rangle_{\text{phot}}\) on the age grids of the hyperz code, and 73% of the old galaxies have \(\langle t_*\rangle_{\text{spec}}\) within a factor of two from \(\langle t_*\rangle_{\text{phot}}\). It seems that these uncertainties are not greater than the others about the photometric age/mass estimates discussed above.

A caveat in our analysis is that the variety of SF history used in photo-z calculation is limited. It is computationally impractical to increase the number of SF history templates by a large factor from that used in this work (eight). However, the dependence on different SF histories has partially been tested by the KA97 model case as described above. We also note that, since we selected old galaxies, the estimates of mean stellar age are expected to be rather insensitive to assumed SF histories. What is important for DTD estimates is the mean stellar ages rather than the details of SF history, provided that the dispersion of stellar age around the mean is not greater than the bin width of DTD measurements. This has already been checked by the calculations of \(\langle \sigma_{t_{\text{phot}}} \rangle\) in section 4.2.

A considerable fraction of the old galaxies have \(A_V > 0.5\) in spite of low star formation activity, as shown in Fig. 1. It might be an artifact due to the uncertainties in \(A_V\) estimates, but in that case it would affect the age estimates. Therefore we removed the old galaxies with \(A_V > 0.5\) and repeated the DTD calculations, which are shown in Table 4 and Fig. 9. The number of the SN candidates is reduced to 48, but the change from the baseline analysis is not significant. The effect of dust extinction on supernova luminosities will be discussed in the next subsection.

We have removed the nuclear region of host galaxies within 1.9 pix radius in our SN candidate search, and it might induce some biases in the age estimates if the removed nuclear regions have considerably different stellar age from the outer regions. The mean fraction of \(i'\) flux within the nuclear region of the old galaxies is 35% of the total isophotal flux, and hence the outer regions are more dominant than the nuclear regions in the photometric redshift calculation. Figure 3 indicates that most of the old galaxies have elliptical morphologies, and they are likely to be the ancestors of the present-day elliptical galaxies (Yamada et al. 2005). It is known that the radial color gradient of local elliptical galaxies is explained by metallicity gradient rather than age gradient (Tamura et al. 2000). The typical metallicity gradient is \(d\log Z/d\log r \sim 0.3\) (Kobayashi & Arimoto 1999), and the effect of metallicity gradient has already been tested, at least partially, by the above examination of the age dependence on metallicity.

4.4. Systematic Uncertainties in Supernova Luminosity

The light curves of SNe are essential for calculations of the visibility time and hence for a rate study. We used the standard light curves of various supernova types as in Oda & Totani (2005). However, we selected SNe Ia in galaxies with old stellar population, and a systematic trend that SNe Ia in old stellar population are fainter than those in star forming galaxies by a peak magnitude difference of \(\Delta M_B \sim 0.3\) has been known (Gallagher et al. 2005; Sullivan et al. 2006).

Extinction in host galaxies may also change the apparent brightness of SNe, and hence the effective luminosity. We assumed a low extinction of \(E(B-V) = 0.05\) (or \(A_V = 0.155\) for the standard Milky Way extinction curve) for SNe Ia, which is reasonable for old galaxies. However, this value is smaller than \(\langle A_V \rangle = 0.31\) of the old galaxies estimated by the photo-z code, though this value should not naively be taken as the extinction of SN flux, as mentioned in section 3.1. It should also be noted that the distribution of old galaxy \(A_V\) is strongly peaked at \(A_V = 0\) (Fig. 1), and the uncertainty in \(A_V\) estimate may have resulted in a larger \(\langle A_V \rangle\) than the real value.

To examine the sensitivity of the DTD estimates to the effective changes of SN luminosity by these effects, we repeated the DTD estimates with the SN Ia light curve shifted by \(\pm 0.3\) mag, and the results are shown in Table 4 and Fig. 9. The difference from the baseline analysis is small, and the uncertainty about the SN luminosity or host galaxy extinction is unlikely to change our main conclusions.

4.5. Uncertainties in the Comparison with the SN Ia Rate of Local Elliptical Galaxies

We assumed 11 Gyr for the mean age of the local elliptical galaxies and hence for the data of Mannucci et al. (2005). We have chosen this value as a mean value
The histograms of the mean stellar ages $\langle t^* \rangle$ (left) and stellar mass $M^*$ (right) of the old galaxies estimated by alternative photometric redshift calculations to the baseline analysis. They are shown in the ratios to those in the baseline analysis. The solid and dashed lines are for the cases of changing to the solar metallicity ($Z = 0.02$) and to the Chabrier IMF, respectively. The dotted line is for the estimates based on a completely different model (KA97) of stellar population synthesis.

Table 5. The logarithmic mean and standard deviation of the ratios of mean stellar age and stellar mass to those in the baseline analysis, for alternative photometric redshift calculations using the solar metallicity, the Chabrier IMF, the KA97 galaxy evolution model, and fixing redshifts at the spectroscopic values.

|                     | solar $Z$ | Chabrier IMF | KA97 | spec |
|---------------------|-----------|-------------|------|------|
| $\log_{10}[\langle t^* \rangle/\langle t^* \rangle_{\text{bl}}]$ | mean 0.04 | 0.004 | −0.09 | −0.11 |
|                     | sigma 0.35 | 0.23 | 0.27 | 0.25 |
| $\log_{10}[M^*/M^*_{\text{bl}}]$ | mean 0.10 | −0.16 | −0.30 | −0.02 |
|                     | sigma 0.15 | 0.17 | 0.28 | 0.15 |

*These quantities should be replaced by $\langle t^* \rangle_{\text{spec}}/\langle t^* \rangle_{\text{phot}}$ and $M^*/M^*_{\text{phot}}$ for the “spec” column.

The “spectroscopic” mean stellar ages ($\langle t^* \rangle$) and stellar masses ($M^*$) versus spectroscopic redshifts, for the old galaxies with available spectroscopic data. See the main text for the definition of these quantities. They are given as the ratios to those by the normal photometric redshift calculations.
of the luminosity-weighted stellar ages of the early type galaxies at $0.05 \leq z \leq 0.2$ estimated by Jimenez et al. (2007), based on the MOPED fits to the SDSS spectra. A slightly smaller but similar age ($\sim 9$ Gyr) is obtained for the SDSS luminous red galaxies at $0.15 \leq z \leq 0.4$ (Barber et al. 2007), when the look back time to the redshift of these galaxies is corrected. The age dispersion around the mean for these early-type galaxies is about 2 Gyr, both for the samples of Jimenez et al. and Barber et al. A systematic uncertainty of $\sim 2$ Gyr in the 11 Gyr data point does not significantly affect the conclusion that the DTD is well described by a power-law.\footnote{Very recently, Gallagher et al. (2008) reported the age and metallicity estimates for the elliptical host galaxies of the local SNe Ia, and the ages estimated by them have a considerably wider distribution than those of Jimenez et al. (2007) and Barber et al. (2007), including a significant fraction of young galaxies with ages less than 5 Gyr. There is no difference in the properties of the SN Ia host galaxies and field elliptical galaxies (Gallagher et al. 2008), indicating that the age difference comes from some systematic uncertainties in the age estimates. The origin of the difference is not clear to us, but it should be noted that the age estimate by Gallagher et al. (2008) is based on $H\beta$, Fe$\lambda5270$ and Fe$\lambda4383$ indices with the spectral library including only single-burst stellar population (SSP). In such analyses, the age estimates are easily affected by a small amount of recent star formation, and they stated in their paper that their age estimates should be regarded as lower limits to the true ages. Their figure 7 shows a strong correlation between the ages and metallicities especially for galaxies younger than 5 Gyr, indicating an effect of the age-metallicity degeneracy in the fittings. The estimates by Jimenez et al. (2007) are based on full spectral information including continuum as well as absorption line indices, allowing any SF history in 11 time bins.}

In the SN Ia rate estimate for the local elliptical galaxies (Mannucci et al. 2005), very faint SNe Ia with the stretch factor $s < 0.8$ are included, reflecting the observed trend that SNe Ia found in old galaxies are subluminous on average (Gallagher et al. 2005; Sullivan et al. 2006). On the other hand, such subluminous SNe Ia are hardly detected in flux-limited high-$z$ supernova searches [see, e.g., Fig. 11 of Sullivan et al. (2006)]. If the fraction of subluminous SNe Ia does not evolve with the delay time, we should correct our DTD data points upward to make an unbiased comparison with the data of Mannucci et al. (2005). However, the fraction of $s < 0.8$ SNe Ia in local elliptical galaxies is $\sim 30\%$ [see again Fig. 11 of Sullivan et al. (2006)], and it does not significantly affect the main conclusions of this work. Furthermore, since our SN candidate sample is at high redshift, it mainly probes shorter delay times of $t_{\text{IA}} \lesssim 2$ Gyr, and there may not be subluminous SNe Ia with such short delay times. In this case, the correction discussed here is not necessary.

5. Implications for the SN Ia Progenitor

5.1. the Double-Degenerate Scenario

The DTDs predicted by the four different theoretical models (Ruiz-Lapuente & Canal 1998; Yungelson & Livio 2000; Greggio 2005; Belczynski et al. 2005) based on the DD scenario are shown in Fig. 12 in comparison with the observed DTD data points. The model curves are normalized at the data point of $t_{\text{IA}} = 11$ Gyr, because the DTD behavior at large delay time is especially important for this scenario from the theoretical point of view (see below). However, the normalization should be regarded as a free parameter and we should compare only DTD shapes between the observations and the models. It is impressive that the predictions by different authors are very close, and in excellent agreement with the observed DTD at $t_{\text{IA}} \gtrsim 0.2$ Gyr. It is not surprising that different authors made similar predictions, because it is a robust and generic prediction of the DD scenario as argued below.

A common feature for DTD models based on this scenario is that the delay time is mainly determined by the time $t_{\text{GW}}$ from the formation of a DD binary (i.e., a binary of two white dwarfs) to a merger after the angular momentum loss by gravitational wave radiation, especially in the long delay time range of $t_{\text{IA}} \gtrsim 1$ Gyr. The general relativity tells us $t_{\text{IA}} \sim t_{\text{GW}} \propto a^3$, where $a$ is the initial separation of the DD binary. If the separation distribution is given by $f_{\text{sep}}(a) \propto a^\alpha$, the DTD should be

$$f_D(t_{\text{IA}}) \propto f_{\text{sep}}(a) \frac{da}{dt_{\text{IA}}} \propto t_{\text{IA}}^{-(3-\beta)/4},$$

and hence $\alpha = -(3 - \beta)/4$. It is known that the distribution of initial binary separation $a_0$ at the time of binary star formation is approximately flat in $\log a_0$, i.e., $f_{\text{sep},0}(a_0) \propto a_0^{-1}$ (Abt 1983). Although there is a significant change and contraction of binary separations during the evolution from a binary star formation to a DD binary (e.g., Greggio 2005), it would be reasonable to assume $\beta = -1$ also for the initial separation of DD binaries. Then we expect $a \sim -1$, as found in the DTD models based on the DD scenario. Though $\beta$ is rather uncertain and model-dependent, the dependence of $\alpha$ on $\beta$ is small. Furthermore, the range of the delay time from 0.1 to 10 Gyr corresponds to a range of $a$ only by a factor of 3.2. Therefore, if $a$ is smoothly distributed in this narrow range, we expect a power-law DTD with $\alpha \sim -1$ in wide and general conditions. This is a general result applicable to any merging phenomena triggered by gravitational wave radiation, such as binary neutron star mergers (Totani 1997), and this is why the DTD models by different authors are quite similar to each other, especially at large delay times. The agreement of the measured DTD with this generic prediction gives a strong support for the DD scenario.

In Fig. 12, we selected the standard DTD model when a few models based on the DD scenario are presented by a single author group [the standard DDS model of Belczynski et al. (2005) and the close-DD model of Greggio (2005)]. The variation models predict slightly different value of $\alpha$, but smooth power-law like DTDs are always common predictions, as expected from the above consideration.

On the other hand, the difference between the DTD predictions by different authors becomes bigger at short delay time ($t_{\text{IA}} \lesssim 0.1$ Gyr), where the delay time is dominated by stellar evolution time scale rather than $t_{\text{GW}}$. There are large uncertainties in the treatments of stellar evolution in
binary population synthesis, and the discrepancy between some of the DTD models and the observed data at this short $t_{Ia}$ range is not serious for the DD scenario.

It is generally assumed that DD binaries are formed through the common envelope evolution phase. If, in addition, DD binaries are formed also from intermediate mass binaries through the classical Roche lobe outflow phase, DD binaries of this channel with large separations may affect the late time behavior of the DTD in the DD scenario (De Donder & Vanbeveren 2003). In other words, the observed DTD gives some constraints on the efficiency of DD binary formation via the Roche lobe outflow phase.

5.2. the Single-Degenerate Scenario

The measured DTD is compared with the theoretical models based on the SD scenario in Fig. 13. Again, the normalization of the models is arbitrary, and we should compare only the shape of the DTD function. Here, the theoretical curves are normalized by $\chi^2$ minimization to the data (our own measurements at 0.1–8 Gyr plus the 11 Gyr data point). In contrast to the DD scenario, the predictions by this scenario are quite different depending on different authors. It is common to this scenario that the delay time is essentially determined by the main-sequence life time of the secondary star in a binary, because other time scales (e.g., accretion phase onto the white dwarf) are much shorter. However, the DTD models shown in this figure are calculated by considerably different methods with a wide range of complexity.

The predictions by Matteucci et al. (2006) and the $Z = 0.05$ model of Kobayashi & Nomoto (2008, hereafter KN08) are close to a simple power-law, and they are relatively in good agreement with the observed DTD, compared with other models. However, it should be noted that the two models are based on the simplest calculations among the models shown here, though such a simple analytical approach is useful to see the general behaviors and in applications for e.g., studies of chemical evolution in galaxies (Kobayashi et al. 1998; Matteucci & Recchi 2001; Matteucci et al. 2006; KN08). In these calculations, the condition for a binary system to evolve to a SN Ia event (i.e., stable accretion up to the Chandrasekhar mass) is determined by the initial masses of the primary and secondary stars, regardless of the binary separation. If the masses are in acceptable ranges, a binary evolves into a SN Ia with a constant efficiency, and no SN Ia is produced in other mass ranges. In such a calculation, the DTD shape is determined by IMF and the distribution of the primary/secondary mass ratio. If smooth functions are assumed for these, a smooth DTD without a characteristic scale of $t_{Ia}$ is obtained. However, a constant SN Ia efficiency within an extended mass range is likely to be an oversimplification. The SN Ia condition should be determined by the combination of the stellar masses and binary separation, and it is natural to expect that there are some characteristic secondary mass scales preferred for success-
Fig. 13. The same as Fig. 12, but for a comparison with the DTD predictions based on the SD scenario. The red curves are predictions of Greggio (2005, solid curve), Matteucci et al. (2006, dotted), and Kobayashi & Nomoto (2008, dashed), based on analytic calculations in which the condition for successful SNe Ia is determined by stellar masses in a binary. The blue curves are predictions of Ruiz-Lapuente & Canal (1998, dotted), Yungelson & Livio (2000, dot-dashed), Belczynski et al. (2005, dashed), and Meng et al. (2008, solid), based on binary stellar population synthesis calculations. The theoretical curves are normalized by $\chi^2$ minimization to the data, and only the DTD functional shapes should be compared in this plot.

ful SN Ia events, which should appear as particular time scales in DTD, rather than a power-law like DTD.

In the KN08 model based on the progenitor model of Hachisu et al. (1996, 2008a), there are two distinct populations of the main-sequence donor channel (WD+MS) and the red-giant donor channel (WD+RG) for short and long delay times, respectively. The relative abundances of the two are determined empirically by fitting to the chemical evolution data, rather than by theoretical modeling. Therefore, the good agreement of the KN08 model with our DTD estimate may partially be a result of this feedback from other observations, indicating that our DTD estimate is also consistent with the chemical evolution data. Though the WD+MS channel is widely considered as the promising SD progenitor of SNe Ia, some theoretical calculations indicate that the SN Ia rate by the WD+RG channel is much lower than that of the WD+MS channel (Yungelson & Livio 1998; Han & Podsiadlowski 2004; Meng et al. 2008, but see also Hachisu et al. 2008b).

The SN Ia condition is determined only by stellar masses also in the standard SD-Chandra model of Greggio (2005), but the mass budget of accretion up to the Chandrasekhar mass is treated in more detail. An interesting feature is the sharp drop of DTD at a large delay time of $\gtrsim 8$ Gyr. SNe Ia with such a large delay time are produced from binary systems with a small secondary mass. Such a low mass star has a small envelope mass that can be used for accretion onto its companion. Therefore, the primary stellar mass must be large enough to ensure that the initial white dwarf mass is sufficiently massive and the white dwarf successfully grows to the Chandrasekhar mass. Consequently, the number of binaries that can evolve to SNe Ia rapidly decreases with decreasing secondary mass. It seems difficult to reproduce a single power-law like DTD up to $\sim 10$ Gyrs if this effect is incorporated.

Finally, predictions of the SG-Ch model of Yungelson & Livio (2000), the standard SDS model of Belczynski et al. (2005), the CLS model of Ruiz-Lapuente & Canal (1998), and the model of Meng et al. (2008) ($\alpha_{CE} = 3$ and $Z = 0.03$) are shown, which are based on detailed calculations of the binary population synthesis, where the calculations start from the initial conditions including the primary and secondary stellar masses and the binary separation. There are a number of parameters and uncertain physical processes in such calculations, and different conditions for SNe Ia are assumed by different authors, leading to vastly different DTD predictions. However, a clear trend is that some characteristic scales of the delay time appear in the DTD, making the DTD shape more complex than the simple analytic models. This is reasonable in realistic conditions, as argued above, and it is theoretically unlikely that a simple power-law like DTD is obtained in
6. Conclusions

6.1. Summary of This Work

We measured the delay time distribution (DTD) of type Ia supernovae by using the statistics of the faint variable objects detected in the systematic variable object survey performed as a part of the Subaru/XMM-Newton Deep Survey project.

Based on photometric redshift calculations using 9 band (\(BVRIz′JK\), \(3.6\ \mu\)m, and \(4.5\ \mu\)m) photometries, we selected 16,492 old galaxies from the SXDS data in the redshift range of \(0.4 \leq z \leq 1.2\), by requiring that their SED can be fit by a single starburst and their ages are significantly greater than the star formation time scales of the bursts. This selection is essential to our work, because stellar age is expected to be a good estimator of Ia delay time in such galaxies. Furthermore, we have two more merits of this selection: (1) delayed SNe Ia are dominant compared with CC SNe and prompt SNe Ia, and (2) extinction effect should be small.

We then selected variable objects associated with these galaxies but having significant offsets from the nuclei of galaxies, to remove the contamination of AGNs. We found 65 variable objects, whose locations with respect to their host galaxies closely trace the profiles of galactic light, and hence the majority of them must be supernovae. Though we do not have spectroscopic confirmation of the SN types, we quantitatively demonstrated that the majority (\(\gtrsim 80\)% of the SN candidates should be SNe Ia, based on the variability luminosity, redshift distribution, and properties of the host galaxies.

Then the DTD in the delay time range of \(t_{\text{Ia}} = 0.1–8\) Gyr is derived by calculating the delay time for each SN Ia candidate from age and star formation history of host galaxies. Combined with the observed SN Ia rate in elliptical galaxies in the local universe, we derive the SN Ia DTD in a range of \(t_{\text{Ia}} = 0.1–11\) Gyr, and found that it can well be described by a simple power-law, \(f_D(t_{\text{Ia}}) = 0.55^{+0.13}_{-0.12}(t_{\text{Ia}}/1\ \text{Gyr})^{-\alpha}\) century\(^{-1}(10^{10}L_{K,0.0})^{-1}\) with \(\alpha = -1.08^{+0.19}_{-0.15}\). Here, the DTD function \(f_D(t_{\text{Ia}})\) is per unit delay time and per unit mass of a single-burst stellar population, and \(L_{K,0}\) (\(K\)-band luminosity at an age of \(11\) Gyr) is used as an observational estimator of the stellar mass. We performed various tests about the systematic uncertainties in this DTD measurement, but the changes of DTD estimates are not large enough to change our main conclusions significantly. We tried a variety of DTD calculations with different prescriptions as shown in Fig. 9, but the decreasing trend of \(f_D(t_{\text{Ia}})\) consistent with \(f_D(t_{\text{Ia}}) \propto t_{\text{Ia}}^{-1}\) at \(t_{\text{Ia}} \sim 0.3–3\) Gyr is found in all cases, and the data points at 0.5–2 Gyr are especially robust against examined systematic uncertainties.

The derived DTD at \(t_{\text{Ia}} \gtrsim 0.2\) Gyr is in excellent agreement with the theoretical predictions based on the DD scenario. The theoretical predictions by different authors are very similar to each other, and a featureless power-law shape is inevitable consequence of the general relativity in this scenario. Therefore we consider that the agreement between the observed and predicted DTDs gives a strong support to this scenario. It indicates that the major contributor to SNe Ia is the DD channel for delay times larger than \(t_{\text{Ia}} \gtrsim 0.1\) Gyr, although some contribution from other channels cannot be excluded.

On the other hand, the predictions by the competing SD scenario are vastly different for different authors. Although the predicted DTDs based on simple analytical approaches have smooth shapes which are broadly consistent with our measurement, predictions based on more detailed binary population synthesis calculations show strong peaks in the DTD shape, which do not fit the observed DTD. This trend can naturally be understood; if there is any preferred scale of the secondary stellar mass for a binary to successfully evolve into a SN Ia, it should be reflected as a characteristic delay time scale in this scenario. Therefore we consider that our result does not favor the SD scenario in general as the major channel to the delayed SN Ia population (\(t_{\text{Ia}} \gtrsim 0.1\) Gyr). However, there are many degrees of freedom and uncertainties in the theoretical modeling based on the SD scenario, and it would be premature to reject the SD scenario simply from our result. Our result should set strong constraints on the model parameter space if the SD channel is responsible for the majority of the delayed SNe Ia, and it would be useful for the future theoretical studies of the SD progenitor models. It is highly desirable to examine physical effects and evolutionary paths that are not taken into account in existing models of binary population synthesis.

6.2. Discussion and Other Implications

In the literature, it has occasionally been argued that the SD scenario is more favored than the DD scenario, but arguments against the DD scenario are not particularly strong. A merger of two white dwarfs may result in an accretion induced collapse rather than a SN Ia (Saio & Nomoto 1985), but theoretical uncertainties are still quite large (Piersanti et al. 2003; Yoon et al. 2007). Many binary systems are proposed as candidates of the SN Ia progenitor in the SD framework, compared with the observed number of DB binaries having total masses
larger than the Chandrasekhar mass (Parthasarathy et al. 2007). However, DD binaries are difficult to detect and the statistics of DD binary searches is not sufficient yet to confirm or reject the DD scenario (Tovmassian et al. 2004; Geier et al. 2007; Napiwotzki 2007). There are some implications for the progenitor from studies of SN Ia remnants (Ruiz-Lapuente et al. 2004; Badenes et al. 2007; Ihara et al. 2007), or from spectroscopic studies (Leonard 2007; Patat et al. 2007a, b; Simon et al. 2007) and archival progenitor searches (Voss & Nelemans 2008; Nelemans et al. 2008; Roels et al. 2008) for nearby SNe Ia. However, conclusive results from these methods have not yet been obtained, mainly because of the limited statistics and theoretical uncertainties.

Another possibility is the SD sub-Chandra scenario (also known as helium ignitors or edge-lit detonations), in which white dwarfs explode as SNe Ia before they reach the Chandrasekhar mass. Since the required amount of accreting mass is smaller than in the SD Chandra scenario, binaries with lower secondary masses can more easily evolve to SNe Ia. This might be useful to overcome the difficulty of the SD scenario to explain SN Ia rate at $t_{\text{Ia}} \gtrsim 10$ Gyr (Greggio 2005). However, this scenario is currently not popular because predicted spectra are in serious disagreement with observations (Hillebrandt & Niemeyer 2000; Livio 2001).

Recent studies (Scannapieco & Bildsten 2005; Sullivan et al. 2006; Aubourg et al. 2007) have tried to model the DTD by two components: the prompt component proportional to SFR and the delayed component proportional to stellar mass (i.e., constant $f_D$). Although our result does not put a strong constraint on the amount of the prompt component, a constant $f_D$ seems to be an oversimplification for the delayed component, since $f_D(t_{\text{Ia}})$ at an intermediate delay time of $t_{\text{Ia}} \sim 1$ Gyr is about 10 times larger than $f_D(11$ Gyr). It should be noted that the prompt Ia population inferred from our data is a considerable fraction ($\sim 20\%$) of all SNe Ia integrated over $t_{\text{Ia}} = 0$–11 Gyr, if we make a modest assumption that $f_D(t_{\text{Ia}})$ at $t_{\text{Ia}} < 0.1$ Gyr is constant at the value of $f_D(0.1$ Gyr). Most of the observed SN Ia rate dependence on galaxy properties can be reproduced by a DTD similar to those predicted by the DD scenario (Greggio 2005; Mannucci et al. 2006). The observed enhancement of SN Ia rate in radio galaxies may require an even higher prompt Ia fraction than that expected from our data or the DD scenario (Della Valle et al. 2005; Mannucci et al. 2006), if the enhancement is due to a recent starburst connected to AGN activity. However, this interpretation seems to be inconsistent with the fact that no enhancement of CC SN rate is observed in radio galaxies (Greggio, Renzini, & Daddi 2008). The statistics of this enhancement is still small ($2\sigma$ level), and it must be confirmed by future observations.

Recently, Pritchet et al. (2008) reported that DTD proportional to $t_{\text{Ia}}^{-0.5 \pm 0.2}$ is implied based on the SNLS data (Sullivan et al. 2006), which seems to be inconsistent with our results. It should be noted that their constraint on DTD is not based on delay time estimate for each SN Ia, but it is indirectly derived from the correlation between SN Ia rate per unit galaxy mass (specific SN Ia rate) and SFR per unit galaxy mass (specific SFR). It is difficult to estimate how large is the systematic uncertainty in such an analysis. Especially, low specific SFR galaxies should be treated with caution. There should be no tight relation between specific SN Ia rate versus specific SFR in such galaxies; specific SFR could change significantly by changing SFR with a fixed stellar mass, but specific SN Ia rate is hardly affected if it is dominated by old stellar population. This should limit the power of this approach to constrain DTD. It should also be noted that the stellar mass estimates in Sullivan et al. (2006) are based on five optical bands ($u^*g'r'i''z''$), although near-infrared bands are essential to reliably estimate stellar masses of galaxies. Another important point is that we obtained a strong constraint on the slope index $\alpha$ by supportively using the SN Ia rate in nearby elliptical galaxies. If we fit our own DTD data, we obtain $\alpha = -0.99^{+0.30}_{-0.27}$. It is important to combine the nearby rate data (large $t_{\text{Ia}}$) and high-$z$ data (small $t_{\text{Ia}}$) to get a strong constraint on the DTD shape in a wide range of the Ia delay time.

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