Two populations of progenitors for type Ia supernovae?

F. Mannucci1*, M. Della Valle2,3, and N. Panagia4,5

1INAF, Istituto di Radioastronomia, Largo E. Fermi 5, 50125 Firenze, Italy
2INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
3Kavli Institute for Theoretical Physics, UC Santa Barbara, CA 93106, USA
4STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA
5Also, INAF, Rome, Italy; and Supernova Ltd., Virgin Gorda, BVI

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ABSTRACT

We use recent observations of the evolution of the type Ia Supernova (SN Ia) rate with redshift (Dahlen et al. 2004), the dependence of the SN Ia rate on the colours of the parent galaxies (Mannucci et al. 2005), and the enhancement of the SN Ia rate in radio-loud early-type galaxies (Della Valle et al. 2005) to derive robust empirical grounds, the distribution of the delay time (DTD) between the formation of the progenitor star and its explosion as a SN. Our analysis finds: i) delay times as long as 3–4 Gyr, derived from observations of SNe Ia at high redshift, cannot reproduce the dependence of the SN Ia rate on the colors and on the radio-luminosity of the parent galaxies, as observed in the local Universe; ii) the comparison between observed SN rates and a grid of theoretical “single-population” DTDs shows that only a few of them are possibly consistent with observations. The most successful models are all predicting a peak of SN explosions soon after star formation and an extended tail in the DTD, and can reproduce the data but only at a modest statistical confidence level; iii) present data are best matched by a bimodal DTD, in which about 50% of type Ia SNe (dubbed “prompt” SN Ia) explode soon after their stellar birth, in a time of the order of 10^8 years, while the remaining 50% (“tardy” SN Ia) have a much wider distribution, well described by an exponential function with a decay time of about 3 Gyr.

The presence in the DTD of both a strong peak at early times and a prolonged exponential tail, coupled with the well established bimodal distribution of the decay rate (Δm_15) and the systematic difference observed in the expansion velocities of the ejecta of SNe Ia in Ellipticals and Spirals, suggests the existence of two classes of progenitors. We discuss the cosmological implications of this result and make simple predictions, which are testable with future instrumentation.

Key words: supernovae: general, white dwarfs, cosmology

1 INTRODUCTION

Type Ia supernovae (SNe) SNe are very important objects in modern cosmology because they are bright sources that can be detected up to large distances and it appears that their intrinsic luminosities can be inferred directly from their light curves. Exploiting these properties, the study of SN Ia at high redshifts has allowed the discovery of the cosmic acceleration (Perlmutter et al. 1998, Riess et al. 1998, Perlmutter et al. 1999). Even though these objects are commonly believed to be associated with the explosion of a degenerate star as a white dwarf (e.g. Hillebrandt & Niemeyer, 2000) the nature of the progenitors of this class of SNe is not firmly established, and several explosion patterns are possible (see, e.g., Branch et al., 1995; Yungelson, 2004) and each of these may dominate at different redshifts. As a consequence, the existence of systematics affecting SNe Ia at different redshifts cannot be ruled out (e.g. Kobayashi et al., 1998; Nomoto et al., 2003) and it is worth being further investigated for possible cosmological implications.

Different explosion models (Greggio & Renzini 1983; Yungelson & Livio 2000; Matteucci & Recchi 2001; Belczynski et al. 2002; Greggio 2004) predict different delay times between the formation of the progenitor system and the SN explosion. Differences in the expected delay times are testable by the observations (Madau, Della Valle & Panagia 1998, Sadat et al. 1998, Dahlen & Fransson 1999) so that constraining the Delay Time Distribution (DTD) will permit one to ascertain the nature of SN Ia progenitors by confirming or excluding some of these models.

* E-mail: filippo@arcetri.astro.it
2 NEW OBSERVATIONAL EVIDENCE

Recently, three important observational results were established:

(i) The evolution of the SN Ia rate with redshift is now measured up to \( z \sim 1.6 \) (Hardin et al. 2004; Pain et al. 2004; Strolger et al. 2003; Madgwick et al. 2004; Cappellaro et al. 2004; Gal Yam & Maoz 2004; Mannucci et al. 2004; Barris & Tonry 2004). The results at the highest redshifts, derived by the GOODS collaboration (Dahlen et al. 2004; Strolger et al. 2004; 2003) show that the SN rate rises up to \( z \sim 0.8 \), when the Universe was 6.5 Gyr old (see panel b of Fig. 1), and decreases afterward. However, the detection of SNe at \( z \sim 1.5 \) is very challenging for the current instrumentation, resulting in a small SN sample (2 SNe in the Dahlen et al. highest redshift bin), and in a very uncertain rate.

This behavior can be compared with the cosmic Star Formation History (SFH) which continues to rise up to \( z \sim 2.5 \), i.e., at a time about 4 Gyr earlier (Madau et al. 1998; Giavalisco et al. 2004). These results have been interpreted by Dahlen et al. (2004) and Strolger et al. (2003) as evidence of a very long delay time (\( \sim 3-4 \) Gyr) between the formation of the stars in the binary system and the explosion of a SN Ia.

(ii) Recently we have measured the SN rate per unit mass in the local Universe (Mannucci et al. 2003), and we have found a very strong dependence of the rate on the (B–K) colour of the parent galaxies: blue galaxies (latest Hubble types) exhibit a SN Ia rate a factor of \( \sim 30 \) higher than that of red galaxies (early types). This result indicates that the delay time must have a wide distribution. In star forming galaxies, the delay time must be as short as the timescale of colour evolution (\( \sim 0.5 \) Gyr), while the existence of supernovae in galaxies without any recent star formation argues that at least some SN Ia have long delay times. For this reason Mannucci et al. (2003), following earlier suggestions (Dallaporta 1973; Della Valle & Livio 1994; Panagia 2000), have proposed, on robust empirical grounds, the existence of two populations of progenitors, one related to the young stellar population, with rates proportional to the recent SFR, the other related to the old stars, with rates proportional to the total stellar mass.

(iii) Della Valle et al. (2005) demonstrated that early-type radio-loud galaxies show a strong enhancement, by a factor of about 4, of the SN Ia rate with respect to the radio-quiet sample, with a constant rate between the samples being rejected at a 99.96% confidence level (see also Della Valle & Panagia 2003). Both the radio activity and the SN rate enhancement are interpreted in terms of episodes of star formation due to merging with small galaxies. Since each episode of radio activity is estimated to last about \( 10^8 \) years (Srinand & Gopal-Krishna 1998; Wan et al. 2000), under this hypothesis the evolutionary time for most SN Ia in radio-loud galaxies must also be around 100 million years.

All the above issues constitute observational links between the epochs of star formation and SN explosion, and, therefore, can be used to constrain the DTD over different timescales. The evolution of the SN Ia rate with cosmic time is sensitive to long timescales (a few Gyr). The dependence of the local rate with the parent galaxy colour samples timescales of the order of the colour evolution of the galaxies, i.e., 0.5–1 Gyr. The relation between SN rate and radio power gives information on the timescales of the order of \( 10^8 \) years, corresponding to the radio activity lifetime.

3 PREDICTING THE SN RATES

The aim of this work is to identify, among the possible DTDs, which ones can simultaneously match all these three results. We will test a set of possible DTDs spanning a broad range of possibilities, using both simple analytical formulations and the results from theoretical works. For each DTD we compute the corresponding expected rates, and compare the results with the above mentioned observational results.

We have assumed that all stars in the 3–8 M\(_{\odot}\) mass range are possible progenitors of SNe Ia (e.g., Nomoto 1994), and have a probability \( \eta \) (Madau et al. 1998) of actually exploding as such within an Hubble time from formation. Madau et al. (1998) have estimated this “explosion efficiency” \( \eta \) to be of the order of 5–10%. Similar results have been obtained by Dahlen et al. (2004) and Greggio (2003). We would like to note here that assuming a different mass range for the mass of the primary would only change the inferred overall explosion efficiency by a factor that depends on the adopted mass limits and the initial mass function (IMF) (see section 2.2) without affecting the conclusions about the nature of the progenitors themselves.

3.1 The evolution with redshift

The evolution of the cosmic SN rate with redshift was modeled by a simple convolution of the assumed DTD with the observed cosmic SFH corrected for dust extinction, as derived by Giavalisco et al. (2004). This is based on a decade of observations at different wavelengths and with various techniques, starting from the pioneering work of Steidel and coworkers (Steidel et al. 1996).

The need for a large correction for dust extinction introduce a difficult uncertainty. The SFH derived directly from UV observations is similar in shape to the corrected one, but is about a factor of 3 lower. As a result, the use of this SFH would produce very similar results but would imply a number of SNe per unit mass in stars three times larger.

We adopted the functional form of the SFH as a function of the cosmic time \( t \) (expressed in Gyr) as given by Strolger et al. (2004), i.e.:

\[
SFH(t) = a \left( t^b e^{-t/c} + d e^{d(t-t_0)/c} \right) \text{M}_\odot/\text{yr/Mpc}^3
\]

where \( a=0.182, b=1.26, c=1.865, d=0.071 \) and \( t_0 \) is the current age of the universe, 13.47 Gyr for the assumed cosmology \( \Omega_M, \Omega_k \) = (0.7, 0.3, 0.7).

To properly take into account the time elapsed between star formation and the creation of white dwarfs that eventually will explode, the DTDs have been convolved with a function of time that, for a given stellar generation, gives the number of white dwarfs accumulating as a result of stellar evolution. Adopting a Salpeter Initial Mass Function (IMF),
half of the white dwarfs from stars in the 3–8 M\(_{\odot}\) mass range form within the first 130 Myr.

For the comparison, we have used the observed rates in Dahlen et al. (2004), Strolger (2003) and Mannucci et al. (2005). The SN rate per unit mass of this latter work was transformed to a SN Ia rate per unit volume by using the local 2dF luminosity function (Cole et al. 2001), obtaining 3.5 \times 10^{-5} SN Ia/yr/Mpc\(^3\).

### 3.2 The dependence on the colour of the parent galaxy

In Mannucci et al. (2005) we have already demonstrated that the dependence of the rate on the colour of the parent galaxy can be reproduced by a simplified model, which comprises two components, one proportional to the SFR (about 40% of the core-collapse SN rate) and one proportional to the total stellar mass. (about 4.4 \times 10^{-4} SNe per year per 10^{10} M_{\odot} of stars). This is consistent with a DTD having two components: a prompt one, exploding with a time scale comparable to that of the core-collapse (CC) SNe; and a second component characterized by a long delay, so that the corresponding rate depends only on the integrated history of the parent galaxy. This result was obtained by using solely observed properties of galaxies and SNe, and, therefore, does not depend on any model of galaxy formation.

Here, we adopt a more refined and accurate approach, and use galaxy formation models to link their observed properties with their past history. We reproduce the properties of the galaxies by calculating a large number of model galaxies (see Table 1) with widely different properties. We used the Bruzual & Charlot (2003) models with different SF histories (from single burst to a rate extended over one full Hubble time), metallicities from 2% to 250% solar, multiple bursts of star formation, and ages between 30 Myr and 13 Gyr. For each model galaxy we compute the present-day (at z=0) (B–K) colour and the present-day SN Ia rate, obtained by convolving the SFH of that galaxy with the assumed DTD.

The dependence of the rate on the colours is obtained by subdividing the galaxies into the same bins of colours, as done for the galaxy sample monitored for SN discoveries as in Mannucci et al. (2005), and averaging the SN rate in each bin.

To compute a meaningful cosmic average to be compared with the observations, we impose that the collection of galaxy models used reproduces the main integrated properties of the observed galaxy population. This was done by assigning appropriate weights to each galaxy model to best match both the observed distribution of (B–K) colour of the galaxies in the local universe and the evolution of the cosmic star formation rate. Many solutions are possible, corresponding to different mixes of galaxy models. The variance in these predictions was therefore estimated by creating many different sets of galaxy samples that, with different mixes of galaxy models, can still satisfy the requirements on the (B–K) colours and the cosmic SFH with different mixes of models and different weights. In all cases the peak-to-peak uncertainty range, represented as a shaded area in the panels (c) of Figures 1–5, is small enough to conclude that these predictions are robust with respect to details of the galaxy models.

For each model, we have computed the value of reduced \(\chi^2\), i.e. \(\chi^2 = \chi^2 / \text{D.O.F.}\) by fully considering the Poisson nature of the errors, and comparing the observed and expected numbers of the events. In the figures we report the associated probability P that the discrepancies are merely due to statistical fluctuations, i.e., the probability that the expected rates are consistent with the observed values. The reported values of \(\chi^2\) and P do not take into account the "model" uncertainties, shown as shaded areas in panels (c) and (d), as they are of systematic rather than statistical nature. Nevertheless, except for the case discussed in section 3 all the models contributing to the shaded areas give agreements comparable to the reported central value.

### 3.3 The dependence on the radio power of the parent galaxy

Della Valle & Panagia (2003) and Della Valle et al. (2003) have demonstrated that the SN Ia rate is higher in radio-loud Ellipticals than it is in radio-quiet ones (about a factor of 4). These authors proposed that both the radio activity and the excess in SN Ia rate are due to merging episodes with small companion galaxies: the accretion of material both fuels the central radio source and produces star formation, which boosts the SN Ia production. In this scenario the observed excess implies that a significant component of the SN Ia population is characterized by delay times as short as those associated with the radio activity.

The lifetime of the radio emission after an episode of star formation in not well known, but several works have proposed that the radio activity and the new episode of star formation are coeval, the excess of SN Ia is directly related to

| Model | SF history | Metallicity |
|-------|------------|-------------|
| mod1  | 0.1 Gyr long Burst | Z⊙ |
| mod2  | exp. decay with \(\tau = 0.2\) Gyr | 40% Z⊙ |
| mod3  | exp. decay with \(\tau = 0.2\) Gyr | Z⊙ |
| mod4  | exp. decay with \(\tau = 0.2\) Gyr | 250% Z⊙ |
| mod5  | exp. decay with \(\tau = 5.0\) Gyr | 2% Z⊙ |
| mod6  | exp. decay with \(\tau = 5.0\) Gyr | 20% Z⊙ |
| mod7  | exp. decay with \(\tau = 5.0\) Gyr | 40% Z⊙ |
| mod8  | exp. decay with \(\tau = 5.0\) Gyr | Z⊙ |
| mod9  | exp. decay with \(\tau = 8.0\) Gyr | 20% Z⊙ |
| mod10 | exp. decay with \(\tau = 8.0\) Gyr | 40% Z⊙ |
| mod11 | exp. decay with \(\tau = 8.0\) Gyr | Z⊙ |
| mod12 | exp. decay with \(\tau = 8.0\) Gyr | 250% Z⊙ |
| mod13 | 50% mod3 + 50% mod1 | Z⊙ |
| mod14 | 90% mod3 + 10% mod1 | Z⊙ |
| mod15 | 97% mod3 + 3% mod1 | Z⊙ |
| mod16 | 99% mod3 + 1% mod1 | Z⊙ |
| mod17 | 50% mod3 + 50% mod1 after 3 Gyr | Z⊙ |
| mod18 | 90% mod3 + 10% mod1 after 3 Gyr | Z⊙ |
| mod19 | 97% mod3 + 3% mod1 after 3 Gyr | Z⊙ |
| mod20 | 99% mod3 + 1% mod1 after 3 Gyr | Z⊙ |
| mod21 | 50% mod3 + 50% mod1 after 10 Gyr | Z⊙ |
| mod22 | 90% mod3 + 10% mod1 after 10 Gyr | Z⊙ |
| mod23 | 97% mod3 + 3% mod1 after 10 Gyr | Z⊙ |
| mod24 | 99% mod3 + 1% mod1 after 10 Gyr | Z⊙ |
4 THE PREDICTIONS OF THE SINGLE-POPULATION DTDS

Fitting exclusively the redshift evolution of SN Ia rates (Dahlen et al. 2004) and Strolger et al. (2004) (see also Strolger et al. 2003) derived indications for long delay times, i.e., a DTD peaked at about 3.4 Gyr with basically no stars exploding during the first two Gyr. This result is the direct consequence of the observation of a decreasing rate at \( z > 1 \). We have tested if such a DTD can reproduce the other two observational evidences. In this case the only parameter that can be varied to simultaneously reproduce the observations is the explosion efficiency \( \eta \). The results are shown in Figure 1, where panel (a) shows the used DTD, panel (b) the evolution of the SN rate with redshift, and panels (c) and (d) the dependence of the SN rate with the (B−K) colour and radio power of the parent galaxies, respectively. It is apparent that such a DTD can reproduce the observed rates in agreement with the observations are below \( 0.1\% \) for the rate-colour plot and below \( 2.5\% \) for the rate-radio power plot. This is true also when considering the uncertainties in the model, shown as a grey area in panel (c); in all cases the probability of agreement remains well below \( 0.1\% \). This demonstrates that the estimated delay times (about 3-4 Gyr) are far too long to reproduce the observed variation with radio power and the enhancement of the rate in the blue galaxies: as no SNe are expected to explode during the first couple of Gyr, this DTD cannot reproduce any dependence of the SN rate on the current SFR.

Looking for a DTD that satisfies all the constraints, we have investigated a large number of possible “single-population” models, i.e., DTDs that can be associated to a single progenitor population and be described by a single analytical law. We used DTDs characterized by different shapes (exponential decline, gaussian shape, and constant over one Hubble time) and characteristic times between 0.1 and 6 Gyr. The results are summarized in the first part of Table 1. None of these simple DTDs can satisfy all of these observational constraints simultaneously. In all cases, at least one of the constraints is not satisfied and the deviations are much greater than the observational uncertainties.

Within this class of models, the observations are best matched by an exponential distribution of delay times with e-folding time of 3 Gyr (see Figure 2). This distribution provides a rather good description of the observed rates as function of redshift (panel b) and of the parent galaxy colours (panel c). However, this model is unable to describe satisfactorily the variation of the rates with the radio-power of the parent galaxy (panel d). These results suggest that while a DTD that extends over several Gyr is needed, an additional contribution at early times (below \( 10^8 \) yr), is necessary to explain all observations.

5 THEORETICAL MODELS

Several authors have derived the DTD from the models of stellar evolution and SN explosion (Greggio & Renzini 1983; Yungelson & Livid 2000; Matteucci & Recchi 2001) and related evidences. In Table 2 we report

| Model                        | \( \eta \) (%) | \( z \) | \( \chi^2_r \) |
|-----------------------------|---------------|------|--------------|
| Single population models    |               |      |              |
| Exponen. decay, \( \tau=1 \) Gyr | 5.3           | 2.7  | 7.2          | 3.7          |
| Exponen. decay, \( \tau=2 \) Gyr | 4.0           | 1.0  | 4.5          | 3.7          |
| Exponen. decay, \( \tau=3 \) Gyr | 3.3           | 0.8  | 4.5          | 3.7          |
| Exponen. decay, \( \tau=6 \) Gyr | 3.2           | 2.1  | 15.7         | 3.7          |
| Constant                     | 2.5           | 4.2  | 29           | 3.7          |
| Gauss at 0.05 Gyr, \( \sigma=0.01 \) Gyr | 6.5           | 3.9  | 32           | 16           |
| Gauss at 0.5 Gyr, \( \sigma=0.1 \) Gyr | 6.0           | 4.0  | 37           | 3.7          |
| Gauss at 1 Gyr, \( \sigma=0.2 \) Gyr | 5.4           | 3.9  | 25           | 3.7          |
| Gauss at 1 Gyr, \( \sigma=1.0 \) Gyr | 4.6           | 2.4  | 9.2          | 3.7          |
| Gauss at 2 Gyr, \( \sigma=0.4 \) Gyr | 4.0           | 1.9  | 23           | 3.7          |
| Gauss at 2 Gyr, \( \sigma=2.0 \) Gyr | 3.7           | 0.5  | 15           | 3.7          |
| Gauss at 3.4 Gyr, \( \sigma=0.68 \) Gyr | 3.6           | 0.2  | 22           | 3.7          |
| Gauss at 4 Gyr, \( \sigma=2.0 \) Gyr | 3.1           | 1.0  | 14           | 3.7          |
| Theoretical models           |               |      |              |
| YL00\(^a\), DD-Ch            | 3.8           | 1.0  | 0.1          | 2.4          |
| YL00, He-ELD                 | 4.5           | 2.2  | 34           | 3.2          |
| YL00, SG-Ch                  | 5.0           | 2.5  | 21           | 3.7          |
| YL00, SG-ELD                 | 4.0           | 0.8  | 11           | 3.7          |
| BBR05\(^b\), SDS, \( \alpha \lambda=0.3 \) | 4.0           | 0.7  | 1.2          | 1.7          |
| BBR05, SWB, \( \alpha \lambda=1.0 \) | 2.2           | 3.5  | 13           | 3.7          |
| G05\(^c\) wide DD \( \tau_{\alpha}=0.4 \beta=-0.9 \) | 4.0           | 1.1  | 0.6          | 3.1          |
| G05 close DD \( \tau_{\alpha}=0.5 \beta=-0.75 \) | 4.0           | 1.0  | 0.2          | 2.9          |
| G05 SD chandra               | 4.1           | 0.9  | 0.6          | 3.3          |
| G05 SD sub-chandra           | 4.3           | 1.2  | 0.3          | 3.0          |
| MR01\(^d\) SD               | 4.7           | 1.5  | 1.6          | 2.2          |

\( ^a \) Yungelson & Livid (2000); \(^b\) Belczynski et al. (2003); \(^c\) Greggio (2003); \(^d\) Matteucci & Recchi (2001)
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The results of the comparison between “theory” and “observations” by changing the only free parameter $\eta$. All models predicting a narrow DTD are ruled out by observations.

Some of the single-degenerate and double-degenerate models, which predict very broad DTDs, spanning delay times from $10^7$ yrs up to $10^{10}$ yrs, give interesting results. This is the case for a number of Greggio (2005) models, both SD and DD (see e.g. Figure 3), the Yungelson & Livio (2000) DD Chandrasekar mass model (see Figure 4), and the Matteucci & Recchi (2001) SD model shown in Figure 5. In all these models the DTD peaks at about $0.6-2\times10^8$ yrs and...
then decays rapidly, roughly like $t^{-1}$, becoming ten times lower after about 1 Gyr. The dependence of the rates with redshift and galaxy colours are satisfactory reproduced, even if in some cases the fast evolution tends to under-predict the SN rate in the reddest galaxies. Most of these DTDs predict that about 5-15% of the SNe explode within the first $10^8$ yrs. As a consequence they produce a SN Ia rate in radio loud galaxies only 10-40% larger then in radio-quiet galaxies, instead of the observed factor of 4. Given the low number of observed events, we cannot exclude these models with a very high statistical confidence level ($P_{\text{radio}}=2-10\%$). As an illustration, let’s consider Greggio (2005) DD model (Figure 3) that well reproduces panels (b) and (c). In this case the peak of the DTD occurs at about $2 \cdot 10^8$ yrs and the fraction of SNe in the first $10^8$ yrs is only 5%. As a consequence the enhancement of the rate in the radio-loud galaxies is only 10%.

Even if these models cannot be ruled out with an high degree of confidence, it is evident that a DTD with both more SNe at early time and a slower evolution afterward is needed to fully account for the observations.

6 TWO POPULATIONS DTDS

For these reasons we considered a set of “two populations” models in which the DTD is obtained as the sum of two distinct functions. In all cases, we added a “prompt” gaussian centered at $5 \times 10^7$ yr to a much slower function, either another gaussian or an exponentially declining function. We will refer to the former component as “prompt” exploders and to latter as “tardy” ones.

Figure 4 shows the results of a model in which 50% of the SNe derive from the “prompt” population, and the remaining 50% from the “tardy” one that consists in an exponentially declining function with characteristic time of 3 Gyr. These results shows that the observational data are better reproduced by a DTD with a peak at short times (below $10^8$ yr) that includes about half of the SN Ia events, and an extension toward very long times, say, 3 Gyr and beyond. Provided that the “tardy” component extends well beyond 3 Gyr, its shape is not well constrained by the fit: exponential decays with characteristic times between 2.5 and 8 Gyr can still provide reasonable fits. These uncertainties will reduce considerably when the SN Ia rates at $z>0.5$ will be measured with greater accuracy.

We notice that a bimodal distribution of delay times should not be regarded as a simple heuristic method to better fit the data, because there are theoretical models which actually predict a bimodal DTD. One of the best examples, see Figure 7, is obtained by Belczynski et al. (2002) with a single-degenerate model with reduced common envelope efficiency ($\alpha \lambda = 0.3$). This model predicts a bimodal DTD which peaks at $10^7$ and $3 \cdot 10^9$ yr, and is due to the explosions of both He and C-O white dwarfs. This model correctly reproduces the evolution of the rate with redshift and its dependence on the colours, and it accounts for the enhancement in the radio-loud galaxies only qualitatively, because its “prompt” peak is centered at $10^8$ yr instead at the best-fitting value of $5 \cdot 10^7$ yr.

Bimodal DTDs can be produced also by models with more than one type of progenitors, for example in which both the single-degenerate and double-degenerate channels are active (see, for example, Nomoto et al., 2003). A bimodal DTD is also naturally produced by the SD model by Kobayashi et al. (1998) in which two different companion

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1 We chose to use “tardy”, rather than “delayed”, to avoid any misunderstanding with the “delayed” detonation model adopted for type Ia supernovae, e.g., Woosley (1990), or more recently, Golombek & Niemeyer (2005)
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stars are present: either a red giant with initial mass of about 1 M⊙ and orbital periods of tens to hundreds days, or a main-sequence star with mass \( \sim 2 - 3 \) M⊙ and periods of the order of a day.

7 DISCUSSION

7.1 Other evidences for bimodality

We have shown that the observational constraints to the SN Ia rates, namely the rate evolution with redshift, the dependence of SN Ia rates with host galaxy colors, and the marked increase of SN Ia rates in radio-loud Ellipticals, are best reproduced if about half of the SNe explode within 10^8 yr from star formation (“prompt” component) while the rest have explosion timescales of a few Gyr (“tardy” component). Particularly from our analysis a number of facts emerge:

- After constraining the delay time distributions to match both the observations at high redshift and in the local universe, we derive a DTD characterized by a strong peak at early times (\( \sim 0.1 \) Mpc) followed by an exponential function with a decay time of about 3 Gyr. Our result rules out all models predicting narrow DTD, pure exponential or pure gaussian DTD and constant DTD.

- There are some single-population models, characterized by broad distributions of delay times (3 orders of magnitude), which can account the observations, but only at a modest statistical confidence level. Given the current uncertainties on the SN rates, they cannot be confidently ruled out.

- The best match to the data is obtained with a bimodal
Figure 6. Same as Figure 1, but for a DTD constituted by equally contributions (50%) of an exponentially declining function with characteristic time of 3 Gyr and a gaussian centered at $5 \times 10^7$ yr and $\sigma = 10^7$ yr. In panel (b) the dotted and dashed lines show, respectively, the contributions from the “prompt” and “tardy” components. The DTD simultaneously reproduces all the SN Ia rate observations.

Figure 7. Same as Figure 1, but for the theoretical DTD predicted by Belczynski et al. (2005) for the single-degenerate model with reduced common envelope efficiency ($\alpha = 0.3$). The best-fitting value of the total efficiency is $\eta = 4.0\%$. In Panel (b) the dotted and dashed lines show, respectively, the contributions from the “prompt” and “tardy” components associated to the two peaks of the DTD. This bimodal DTD appears to reproduce reasonably well the SN Ia rate observations, although the position and the intensity of the “prompt” peak produce only a small enhancement of the rate in the radio-loud Ellipticals.

DTD. However, the existence of a bimodality in the DTD does not directly imply the existence of two distinct populations of SNe. This bimodality might be related to the bimodal distribution of $\Delta m_{15}$ (the magnitude decline of the light curve between its maximum and 15 days later) exhibited by SNe Ia in Ellipticals and in spirals (Della Valle et al. 2005, their fig. 6, see also Altavilla et al. 2004). If this is the case, the bimodality of the DTD gives support to earlier suggestions which interpreted the bimodal behavior of $\Delta m_{15}$ in terms of an age sequence (Ruiz-Lapuente et al. 1995, Hamuy et al. 1996, Howell et al. 2001, van den Berg et al. 2005), with metallicity being less important (Ivanov et al. 2000, but see Kobayashi et al. 1998). In this scenario it is likely to expect that the bright SN events (with small $\Delta m_{15}$) are preferentially associated with the “prompt” population, which is more common in spiral and irregular galaxies (Hamuy et al. 2000), while the faint and rapidly decaying objects are more easily found in the “tardy” component, which is more common in early-type galaxies. If this is true, then we expect that SN Ia in radio-loud Ellipticals, where the “prompt” population is expected to dominate, show $\Delta m_{15}$ smaller that...
those in the radio-quiet Ellipticals. This issue is discussed in Della Valle et al. (2005) (see their fig. 6). The small number of events with published value of $\Delta m_{15}$ prevents us from reaching any definite conclusion.

• Finally we notice that the existence of a continuous sequence in the spectroscopic properties of maximum light spectra of SNe Ia (Branch et al. 2006) is not at variance with the existence of two different evolutionary paths to rise SNe Ia, as our results may suggest. What is relevant for our analysis is how the spectroscopic properties of SNe Ia correlate with the stellar population from which the SN progenitors originate. The systematic differences measured in the expansion velocities of the ejecta of SNe Ia occurring in Ellipticals and Spirals (Branch & van den Bergh 1993; Benetti et al. 2005) are indeed fully consistent with our results.

7.2 Bimodality and stellar mass

We note that the main sequence lifetime is about $5 \times 10^8$ yr for a star of $3 M_\odot$, $10^7$ yr for $5.5 M_\odot$ and about $4 \times 10^7$ yr for $8 M_\odot$ (e.g., Girardi et al. 2000). Therefore, the SNe of the “prompt” peak, which include about 50% of the total number of SN Ia events and explode within $10^8$ yr from star formation, must all derive from stars with masses above $5.5 M_\odot$. Also, for a Salpeter IMF, the number of stars between 5.5 and $8 M_\odot$ are about a third of those between 3 and 5.5$ M_\odot$. This implies that the SN Ia efficiency for higher mass progenitors ($5.5-8M_\odot$) is about 3 times higher that for lower mass progenitors (3–5.5$ M_\odot$). Therefore, given an overall efficiency of 4.5% (see Figure 6), it follows that the efficiency for higher mass stars is $\eta(5.5-8M_\odot) \sim 6.8\%$, and the one for lower mass stars is $\eta(3-5.5M_\odot) \sim 2.3\%$. Therefore, the requirement that about 50% of the SN Ia must explode within $10^8$ yrs is that the efficiency and the characteristic delay time are expected to change considerably at $\sim 5.5 M_\odot$.

It is important to realize that the explosion efficiency of the “prompt” SN Ia is determined unambiguously by their number and the mass range of the progenitors. On the other hand, if the remaining 50% SNIa, i.e. the “tardy” component, could arise not only from stars in the range 3–5.5$ M_\odot$, but also from stars of lower masses, then their inferred explosion efficiency for low mass stars would also decrease, because the available pool of stars would increase whereas the number of “tardy” SNe does not.

We cannot draw conclusions on whether this change of the efficiency at about $5.5 M_\odot$ is due to a different physical process (e.g., SD vs. DD) or to one and the same process operating in separate regions of the parameter space (e.g., systematic differences of the binary systems as a function of the stellar mass). For example, the theoretical models producing wide DTDs described in section 6 are not able to resolve this ambiguity because of both uncertainties in the model assumptions and possible coexistence of different physical processes. However, we are confident that a judicious analysis of data obtained for a large sample of SN Ia over a suitably wide interval of redshifts will make it possible to clarify this issue.

7.3 Consequences of the bimodality on Cosmology

In addition to providing essential clues to the nature of SN Ia progenitors, our results have also important implications for cosmology:

• The fraction of SNe coming from either of the two populations changes with cosmic time, as can be seen from Figure 6: the “tardy” SNe dominate at $z<1.3$ and the “prompt” SNe above this limit. The ratio of the “prompt” SN rate to that of the “tardy” SNe changes from 0.5 in the local universe to about 1.2 at $z=1.5$. Similar results are obtained for the single-degenerate model by Belczynski et al. (2002) (Figure 7).

• It is reasonable to expect that the two populations of SNe can be distinguished also by some intrinsic properties. As an example, it is possible that “prompt” SNe Ia are, on average, more affected by dust extinction than the “tardy” component, as they must explode closer to the formation cloud (Sullivan et al. 2003). In this case, the average properties of SNe Ia are expected to change with redshift, especially at $z>1$ when the “prompt” SNe become common. The Hubble diagrams used to derive information on the cosmological parameters (e.g., Riess et al. 2004) are, up to now, mostly based on SNe at $z<1$ and, therefore, are expected to be dominated by the “tardy” population. As the ratio between the two different flavors of type Ia SNe changes with cosmic time, evolutionary effects should become important at high redshifts (Livio & Riess, 2006).

• The luminosity-decline rate relation for SN Ia (Pakossi 1977; Phillips 1993; Hamuy et al. 1995; Phillips et al. 1993) is derived in the local universe and, therefore, under this scenario, is dominated by the “tardy” SNe. The evidence for a cosmological acceleration relies on the assumption that the same relation holds also at high redshift (see Rowan-Robinson 2002 and Leibundgut 2004 for a discussion). If the two populations follow slightly different relations, a bias is expected to emerge as a function of redshift, especially when the “prompt” population becomes dominating, at $z \sim 1.2$. Thus, a confident use of SNe Ia for cosmology measurements at $z>1$ would require a good understanding of the differences in properties of the two populations.

7.4 Bimodality and metallicity evolution

The existence of two populations of SN Ia has direct consequences also on the chemical evolution of the universe.

• “Prompt” type Ia, having a redshift distribution similar to the CC SNe, dominate the SN Ia population at high redshifts. Therefore, in the early Universe the production of Fe is expected to follow that of Oxygen, and the O/Fe abundance ratio should be relatively constant but appreciably higher than in the local Universe. When the SN Ia “tardy”
component starts dominating, i.e. past the SFH peak at \( z \sim 2 \), the Fe production is boosted and the O/Fe ratio is expected to decrease rapidly to approach the “solar” values around redshifts \( < 0.5 \). These aspects have recently been discussed in some detail by Scannapieco & Bildsten (2002), who for their model calculations adopted the simplified description of the SN Ia rates as derived by Mannucci et al. (2003) in terms of a component proportional to the star formation rate (SFR) and another one that is proportional to the total stellar mass.

- It is known that the intra-cluster medium is relatively rich in iron ([Fe/H] \( \sim -0.5 \)) and that the metallicity shows a very mild evolution with redshift (Tozzi et al., 2003). The observed iron mass is about a factor of 6 larger than could have been produced by core-collapse SNe (Maoz & Gal-Yam 2004) and a factor of 10 larger than that produced by the current rate of SN Ia (Renzini, 2004). The “two populations” model naturally explains these observations, as the current rate of SN Ia (Renzini, 2004) and a factor of 10 larger than that produced by core-collapse SNe (Maoz & Gal-Yam 2004) in terms of a component proportional to the star formation rate (SFR) and another one that is proportional to the total stellar mass.

- In the models predicting either bimodal or wide DTDs, “prompt” type Ia and Core-Collapse (CC) SNe are characterized by similar delay times and both trace the cosmic star formation history. At high redshifts the SN Ia “tardy” component tends to disappear and therefore we predict that the rate ratio CC/Ia steadily increases with redshift, as shown in Figure 8, from a value of about 3 in the local universe to about 9 at \( z \approx 4 \). On the contrary, the “single-population” model in Figure 1 predicts a much faster evolution of the CC/Ia ratio, which is expected to become larger than 10 already at \( z \sim 1.5 \).

Measuring the SN rates and their CC/Ia ratio at high redshifts will be a very interesting task for the upcoming James Webb Space Telescope and giant ground-based telescopes and will permit to confirm or discard these predictions.

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7.5 Predictions

The existence of the “prompt” and “tardy” populations of type Ia SNe can be tested by two observations:

- The SN Ia rate is expected not to decrease significantly moving toward high redshifts up to \( z \sim 2 \), at which the cosmic star formation history has its broad peak. As a consequence, it should be possible to detect SNe Ia up to high redshifts, \( z \sim 5 \) so as to discriminate among different cosmological models. In particular, at \( z > 2 \) the SN Ia rate should be nearly constant at a level of about \( 10^{-4} \) SN yr\(^{-1} \) Mpc\(^{-3} \) (see Figure 6). Such a rate can be reduced only if the effects of metallicity evolution become important at \( z \sim 1 \), and if the changing in metallicity has an important effect in the explosion rate as predicted by Kobayashi et al. (1998).

Figure 8. Ratio of the rates of the CC to Ia SNe as a function of the redshift. The white and black dots are observed values (Mannucci et al. 2002, Dahlen et al. 2004). The lines show the predictions of the gaussian “single-population” model in figure 1 (dashed), the Yungelson & Livio (2000) model in figure 4 (dotted), and the “two-populations” in figure 6 (solid). The predictions use a Salpeter IMF and mass ranges of 3-8M\(_\odot\) (SNe Ia) and 8-40M\(_\odot\) (CC SNe), and are scaled to match the observed values.
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