Type Ia Supernova Rates Near and Far

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Abstract.
Recently, three important observational results were established: (a) The evolution of the SNIa rate with redshift is now measured up to $z \sim 1.6$ and the results at the highest redshifts, derived by the GOODS collaboration show that the SN rate rises up to $z \sim 0.8$, when the Universe was 6.5 Gyr old, and decreases afterward. (b) The rate of supernova explosions of the different types as a function of the galaxy (B-K) and the galaxy mass have been determined. It is found that the rates of all SN types, including Ia, Ib/c and II, show a marked increase with the star formation activity. (c) An analysis of SNIa events in early-type galaxies has provided conclusive evidence that the rate of SNIa in radio-loud galaxies is much higher than the rate measured in radio-quiet galaxies. This result suggests that repeated episodes of interaction and/or mergers of early-type galaxies with dwarf companions are responsible for supplying an adequate number of SNIa progenitors to the stellar population of elliptical galaxies.

On this basis we have discussed the distribution of the delay time (DTD) between the formation of a SNIa progenitor star and its explosion as a SNIa. Our analysis finds: i) models with long delay times, say 3-4 Gyr, cannot reproduce the dependence of the SNIa rate on the colors and on the radio-luminosity of the parent galaxies; ii) the dependence of the SNIa rate on the parent galaxy colors requires models with a wide DTD, spanning the interval 100 Myr to 10 Gyr; iii) the dependence on the parent galaxy radio-luminosity requires substantial production of SNIa at epochs earlier than 100 Myr after the birth of a given stellar generation; iv) the comparison between observed SN rates and a grid of theoretical "single-population" DTDs shows that only a few of them are marginally consistent with all observations; v) the present data are best matched by a bimodal DTD, in which about 50% of type Ia SNe ("prompt" SNIa) explode soon after their stellar birth, in a time of the order of 100 Myrs, while the remaining 50% ("tardy" SNIa) have a much wider distribution, well described by an exponential function with a decay time of about 3 Gyr. This fact, coupled with the well established bimodal distribution of the decay rate, suggests the existence of two classes of progenitors and/or explosive channels. We discuss the cosmological implications of this result and make simple predictions.

Keywords: Supernovae: General, Stars: Evolution, Binaries: General, Supernovae: Progenitors, Galaxies: Abundances, Intergalactic Medium, Cosmology: miscellaneous

PACS: 97.60.Bw, 97.60.-s, 97.80.-d, 98.35.Bd, 98.62.Ra, 98.80.-k

1. INTRODUCTION

Type Ia supernovae (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 SNIa 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 SNIa progenitors 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 SNIa 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 (e.g. Greggio & Renzini 1983, Yungelson & Livio 2000, Matteucci & Recchi 2001, Belczynski, Bulik & Ruiter 2005, Greggio 2005) predict different delay times between the formation of the progenitor system and the SN explosion. Differences in the expected delay times are testable with the observations (e.g. 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 SNIa progenitors by confirming or excluding some of these models.

2. NEW OBSERVATIONAL EVIDENCE

In the last few years, three important observational results were established:

(1) The evolution of the SNIa rate with redshift is now measured up to z~1.6 (Hardin et al. 2000, Pain et al. 2002, Strolger 2003, Madgwick et al. 2003, Cappellaro et al. 2004, Gal-Yam & Maoz 2004, Mannucci et al. 2005, Barris & Tonry 2006,Neill et al. 2006). The results at the highest redshifts, derived by the GOODS collaboration (Dahlen et al. 2004, Strolger et al. 2004, 2005) show that the SN rate rises up to z~0.8, when the Universe was 6.5 Gyr old (see panel b of Fig. 1), and decreases afterward. This behavior can be compared with the cosmic Star Formation History (SFH) which continues to rise up to z~ 2.5, i.e., at a time about 4 Gyr earlier (Madau, Pozzetti & Dickinson 1998, Giavalisco et al. 2004). These results have been interpreted by Dahlen et al. (2004) and Strolger et al. (2005) as evidence of a very long delay time (~ 3 – 4 Gyr) between the formation of the stars in the binary system and the explosion of a SNIa.

(2) Recently, we have determined the SN rates per unit mass in the local Universe (Mannucci et al. 2005), finding a very strong dependence of the rates on the (B−K) colour of the parent galaxies: blue galaxies (the latest Hubble types) exhibit a SNIa rate a factor of ~ 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 at least as short as the timescale of colour evolution (~ 0.5 Gyr), while the existence of supernovae in galaxies without any recent star formation argues that some SNIa have long delay times. For this reason Mannucci et al. (2005), following earlier suggestions (e.g., Dallaporta 1973, Della Valle & Livio 1994, Panagia 2000), have proposed the existence of two populations of progenitors, one related to the young stellar population, with rates proportional to the recent star formation rate (SFR), the other related to the old populations, with rates proportional to the total stellar mass accumulated over time, i.e. the integral of the SFR over time.

(3) Della Valle et al. (2005) demonstrated that early-type radio-loud galaxies show a strong enhancement, by a factor of about 4, of the SNIa rate with respect to the
radio-quiet sample, and that the hypothesis of an equal rate between the samples can be 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 (Srianand & Gopal-Krishna 1998, Wan, Daly & Guerra 2000), the evolutionary time for most SNIa 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 in that: (i) The evolution of the SNIa rate with cosmic time is sensitive to long timescales (up to several Gyr). (ii) 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., up to 0.5-1 Gyr. (iii) 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. SINGLE POPULATION DTD

Looking for a DTD that satisfies all 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 (Mannucci, Della Valle & Panagia, 2006). 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. None of these simple DTDs can satisfy all of the observational constraints simultaneously. Within this class of models, the observations are best matched by an exponential distribution of delay times with e-folding time of 3 Gyr. This distribution provides a rather good description of the observed rates as function of redshift and of the parent galaxy colours. However, this model is unable to describe satisfactorily the variation of the rates with the radio-power of the parent galaxy. These results indicate 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.

Some of the single-degenerate and double-degenerate models, which predict very broad DTDs provide interesting results. This is the case for a number of Greggio (2005) models, both single-degenerate (SD) and double-degenerate (DD), Yungelson & Livio (2000) DD Chandrasekar mass model, and the Matteucci & Recchi (2001) SD model. In all these models the DTD peaks at about $0.6 - 2 \times 10^8$ yr and then decays rapidly, roughly like $t^{-1}$, dropping by a factor of 10 after about 1 Gyr. The dependence of the rates with redshift and galaxy colours are satisfactorily reproduced, although in some cases the fast evolution tends to under-predict the SNIa rate in the reddest galaxies. However, these DTDs predict about 5-15% of SNIa to explode within the first $10^8$ yrs. As a consequence, they produce a SNIa rate in radio loud galaxies only 10-40% higher than in radio-quiet galaxies, instead of the observed factor of 4. Even if these models cannot be ruled out with an high degree of confidence, it is clear that a DTD with both more SNIa explosions at early times and a slower evolution afterward is needed to fully account for the observations.
FIGURE 1. The SN rates for a DTD constituted by equal contributions (50%) of an exponentially declining function with e-folding time of 3 Gyr and a gaussian centered at $5 \times 10^7$ yr and $\sigma = 10^7$ yr. Panel (a): the DTD itself (number of SNIa per unit time after star formation); Panel (b): the evolution of the rate along the cosmic age. The solid curve is the prediction for the considered DTD. Data are from Mannucci et al. (2005; open circle), Strolger et al. (2004; star), Dahlen (2004; dots, with black error bars for $1\sigma$ statistical errors, and the gray bars for systematic uncertainties). In panel (b) the dotted and dashed lines show the contributions from the “prompt” and “tardy” components, respectively. $P$ is the statistical probability of agreement estimated from the statistical errors only. Panel (c): the predictions (solid line and triangles) for SNIa rates as a function of the parent galaxy (B−K) colour, expressed in SNe per century per $10^{10} M_\odot$ of stellar mass (SNuM). The dots and the dashed line show the observational data from Mannucci et al. (2005). Panel (d): SNIa rates in early-type galaxies as a function of the radio power of the parent galaxy. The black dots are the observed SN rates in Della Valle et al. (2005) with $1\sigma$ Poisson error.
4. 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 1 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 an e-folding 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 SNIa 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 SNIa rates at $z \geq 0.5$ will be measured with greater accuracy.

We note that a bimodal distribution of delay times should not be regarded as just a heuristic method to fit the data, because there are theoretical models which actually predict a bimodal DTD. One of the best examples (see Figure 7 in Mannucci et al. 2006) is provided by Belczynski et al. (2005) SD model with reduced common envelope efficiency ($\alpha \lambda = 0.3$). This model predicts a bimodal DTD which peaks at $10^8$ and $3 \times 10^9$ yr, and includes both He and C-O white dwarf explosions. This model correctly reproduces the evolution of the rate with redshift and its dependence on the colours, but 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 $5 \times 10^7$ yr.

Bimodal DTDS can also be produced 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 stars are present: either a red giant with initial mass of about 1 M$_\odot$ and orbital periods of tens to hundreds days, or a main-sequence star with mass $\sim 2 - 3$ M$_\odot$ and periods of the order of a day.

5. DISCUSSION

We have shown that the observational constraints to the SNIa rates, namely the rate evolution with redshift, the dependence of SNIa rates with host galaxy colors, and the marked increase of SNIa rates in radio-loud Ellipticals, are best reproduced if about half

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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)
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). We would like to stress that while the exact shape of these two distributions cannot be determined accurately, the requirement of 50% prompt and 50% tardy SNIa is unavoidable.

Similar conclusions have been reached by Sullivan et al. (2006) from an analysis of a sample of 124 SNIa from the Supernova Legacy Survey (SNLS) distributed over $0.2 < z < 0.75$. They also found that passive galaxies, with no star formation, preferentially host faster declining/dimmer SNIa, while brighter events are found in systems with ongoing star formation.

### 5.1. Bimodality and stellar mass

We note that the main sequence lifetime is about $5 \times 10^8$ yr for a star of $3 M_\odot$, $10^8$ 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 SNIa 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 SNIa efficiency for higher mass progenitors ($5.5$–$8 M_\odot$) is about 3 times higher that for lower mass progenitors (3–5.5M$_\odot$). Therefore, given an overall efficiency of 4.5%, it follows that the efficiency for higher mass stars is $\eta(5.5$–$8 M_\odot) \sim 6.8\%$, and the one for lower mass stars is $\eta(3$–$5.5 M_\odot) \sim 2.3\%$. Therefore, the requirement that about 50% of the SNIa explode within $10^8$ yrs implies that the efficiency and the characteristic delay time are expected to change considerably for stellar masses around $5.5 M_\odot$.

It is important to realize that the explosion efficiency of the “prompt” SNIa is determined unambiguously by their number and the mass range of the progenitors as directly implied by the observations. On the other hand, if one allows the remaining 50% SNIa, i.e. the “tardy” ones, to arise also from stars with masses lower than $3 M_\odot$, then their inferred explosion efficiency 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 the 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, it could be that the binary fraction for primary stars with masses above $5.5 M_\odot$ is markedly higher than for lower mass stars. Or it could be that the distribution of secondary star masses is more skewed toward masses close to the primary star mass and, therefore, the mass transfer be more efficient and faster (see Pinsonneault & Stanek 2006 for a discussion).

The currently existing models (e.g. Greggio 2005, Belczynski et al. 2005, Nomoto et al. 2003) 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 SNIa over a suitably wide interval of redshifts will make it possible to clarify this issue.
5.2. Consequences of the bimodality on Cosmology

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

- The fractions of SNe coming from the two populations change with cosmic time, as can be seen from Figure 1: 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 Belczynski et al. (2005) SD model.

- It is conceivable that the two populations of SNe can be distinguished also by some intrinsic properties. As an example, it is possible that “prompt” SNIa are, on average, more affected by dust extinction than the “tardy” component, as they must explode closer to the formation cloud (e.g. Sullivan et al. 2003, Mannucci, Della Valle & Panagia 2007). In this case, the average properties of SNIa are expected to change with redshift, especially at $z > 1$ when the “prompt” SNe become more 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 SNIa changes with cosmic time, evolutionary effects should become more important at higher redshifts (Riess & Livio, 2006).

- The luminosity-decline rate relation for SNIa (Pskovskii 1977, Phillips 1993, Hamuy et al. 1996, Phillips et al. 1997) 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 reliable use of SNIa for cosmology measurements at $z > 1$ would require a good understanding of the differences in properties of the two populations.

5.3. Bimodality and metallicity evolution

The existence of two populations of SNIa has direct consequences also on the chemical evolution of the Universe:

- “Prompt” SNIa, having a redshift distribution similar to the CC SNe, dominate the SNIa 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 is expected to be relatively constant but appreciably higher than in the local Universe. When the SNIa “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 $<\sim 0.5$. These aspects have recently been discussed in some detail by Scannapieco & Bildsten (2005) who for their model calculations adopted the simplified description of the SNIa rates as derived by Mannucci et al. (2005) in terms of a component proportional to the star formation rate (SFR) and another one...
FIGURE 2. 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. 2005, Dahlen et al. 2004). The lines show the predictions of the gaussian “single-population” model (i.e. a model in which the DTD is a narrow gaussian centered at 3-4 Gyr; dashed line), Yungelson and Livio (2000) DD Chandrasekar mass model (dotted line), and the “two-populations” shown in Figure 1 (solid line). The predictions use a Salpeter IMF and mass ranges of 3-8M_{⊙} (SNIa) and 8-40M_{⊙} (CC SNe), and are scaled to match the observed values.

that is proportional to the total stellar mass. More recently, Matteucci et al. (2006) have included the bimodal DTD for SNIa in chemical evolution model calculations, to find that this scenario is fully consistent with the main chemical properties of galaxies of various morphological types.

- It is known that the intra-cluster medium is relatively rich in iron ([Fe/H]~ −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 SNIa (Renzini, 2004). The “two populations” model naturally explains these observations, as the current type Ia rate is just the long-time declining tail of a SN distribution that peaked at early cosmic times. The amount of observed iron and its redshift evolution is reproduced by assuming an average age of the stars in clusters of 10 Gyr (see Matteucci et al. 2006).

5.4. Predictions

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

• The SNIa rate is expected not to decrease significantly moving toward high redshifts up to z~2, at which the cosmic star formation history has its broad peak. As a consequence,
it should be possible to detect SNIa up to high redshifts, say, \( z \sim 5 \) so as to discriminate among different cosmological models. In particular, at \( z > 2 \) the SNIa rate should be nearly constant at a level of about \( 10^{-4} \) SN yr\(^{-1}\) Mpc\(^{-3}\) (see Figure 1). 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).

- 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 SNIa “tardy” component tends to disappear and therefore we predict that the rate ratio CC/Ia steadily increases with redshift, as shown in Figure 2, from a value of about 3 in the local Universe to about 9 at \( z \geq 4 \). On the contrary, a “single-population” model 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 verify these predictions.

**ACKNOWLEDGMENTS**

NP acknowledges partial support from STScI, through DDRF grant #82367, and from INAF - Observatory of Rome that allowed him to attend this conference.

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