The cosmic rate of supernovae and the range of stars ending as Type Ia SNe

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ABSTRACT

The present cosmic rate of Type Ia supernovae (SNeIa) suggests that about 6% of all stars in binary systems with primaries in the initial mass range $3 - 9 \, M_\odot$ end up as SNeIa. If that is confirmed, the unavoidable conclusion is that SNeIa can only be explained by the single degenerate scenario. At most 1% of stars in binary systems in the above range end up as CO + CO WD pairs, with total mass equal to or larger than the Chandrasekhar mass. Given that the number of mergers from pairs of CO + He WDs that reach the Chandrasekhar mass is even lower, the conclusion strongly favors binaries containing just one CO WD as the progenitors of SNeIa, since the SNeIa production efficiency (relative to the instantaneous star formation rate) predicted for double degenerate (DD) pairs lies more than $3\sigma$ below the observational data, and the DD scenario can be rejected at more than 99% confidence level. Only if the SFR measurements from $z \sim 0.1$ to $z \sim 0.5$ are being underestimated by a factor of 6 while SNeIa rates are not, can we escape the above conclusion. We evaluate the numbers and characteristics of double WD systems with different chemical compositions (CO and He WDs) that should form and compare them with the observations, in order to check our predictions. Our conclusions appear robust after that test.

Subject headings: cosmology: supernovae: general — binaries: close binaries — stars: white dwarfs
1. Introduction

The evolution of intermediate and low-mass stars in binary systems is a complex subject that has, however, enormous importance in astrophysics. Of their way to the final end, a bulk of information is available from observations on the processes undergone by binaries as they evolve, i.e. common-envelope phases, accretion, outburst.

A relevant new piece of information comes from the consideration of the number of Type Ia supernova explosions (SNeIa) that occur per unit mass spent in forming stars in different environments. So far, the exploration of the issue was restricted to nearby galaxies, where the combination of SNeIa statistics with star formation rate (SFR) history is poorly known.

The approach explored here is to take the average of star formation history in redshift space and use the information on cosmic SNeIa rate to infer how many stars in binaries from low to intermediate mass end up as SNeIa. This indirect approach started a few years ago (Ruiz–Lapuente, Burkert, & Canal 1995; Ruiz–Lapuente, Canal, & Burkert 1997; see also Madau, Della Valle, & Panagia 1998; Sadat et al. 1998; Ruiz–Lapuente & Canal 1998; Yungelson & Livio 1998, 2000; Kobayashi et al. 1998; Dahlen & Fransson 1999; Ruiz–Lapuente, Cassé, & Vangioni–Flam 2000) and it can help us to determine the nature of the progenitors of SNeIa.

We evaluate the number of SNeIa exploding per unit comoving volume, in redshift space, and relative to the mass going into forming stars in the Universe. Despite the uncertainties still involved, the last years have nevertheless brought some crucial information.

As we will see, if the efficiency of binaries in ending as SNeIa is 6% of the stars between $3 - 9 M_\odot$, no other alternative than the single degenerate scenario appears as a reasonable
candidate to explain those explosions. The modeling on which that conclusion is based stands comparison with the statistics of the white dwarf (WD) pairs actually observed.

2. The star formation rate and the SNeIa production efficiency

In the last few years we have started to learn about the cosmic history of the star formation process, and several groups (Madau et al. 1996; Steidel et al. 1998; Hughes et al. 1998; Madau, Pozzetti, & Dickinson 1998; Blain et al. 1999) have begun to derive the global star formation rate $\dot{\rho}_*(z)$. At the same time, the first measurements of the global SNeIa rates, $\mathcal{R}_{Ia}(z)$, are being performed (Pain et al. 1996; Hardin et al. 2000; Hamilton 1999; Hamuy & Pinto 1999; Pain et al. 2000). The SNeIa rate is doubly related to the SFR: through the time delay between formation of the SNeIa progenitor systems and explosion, and through the fraction of stars (binaries in this case) that give rise to SNeIa. The comparison between $\dot{\rho}_*(z)$ and $\mathcal{R}_{Ia}(z)$ thus contains key information on the nature of the so far elusive SNeIa progenitors.

The work of Madau et al. (1996), based on the UV luminosities of galaxies in the Hubble Deep Field, complemented that of Lilly et al. (1995, 1996) at optical wavelengths in showing that the star formation activity steadily increases with $z$ from the local, present–day Universe, up to $z \sim 1.5$. The original claim that $\dot{\rho}_*(z)$ peaks there to fall again at higher $z$ has later been revised, in particular on basis to data at long wavelengths that would indicate that the star formation regions at high $z$ are enshrouded in dust (see Hughes et al. 1998, for instance). $\dot{\rho}_*(z)$ would level–off beyond $z \simeq 1.5 - 2$, up to much higher redshifts. Observations in the submillimeter range (Blain et al. 1999), ISO measurements of the extragalactic background light (Rowan–Robinson et al. 1997; Flores et al. 1998; Elbaz et al. 1999), and the FIRAS and DIRBE experiments on board of COBE (Dwek et al. 1998; Fixsen et al. 1998), do in principle lift the veil on the star formation activity.
in dust–obscured regions, but there is no redshift identification of the emission detected. Measurement of the SN rates at high $z$ then would help to trace the star formation history. SNeIa are the most luminous ones. Thus, knowledge of the characteristic time delays between formation of their progenitor systems and explosion is most relevant.

The measurements of the cosmic evolution of the SNeIa rate now extend up to $z \sim 0.55$, and there are already preliminary results for $z \simeq 1.1$. Current results are summarized in Table 1. By combining our knowledge of $\mathcal{R}_{Ia}(z)$ with that of $\dot{\rho}_*(z)$, we can now gain new insight on the nature of the SNeIa progenitor systems. We introduce for that the “efficiency” $\mathcal{E}_{SNeIa}(z)$ of SNeIa production referred to the SFR, both per unit of comoving volume:

$$\mathcal{E}_{SNeIa}(z) = \mathcal{R}_{Ia}(z) \, yr^{-1} \, Mpc^{-3} / \dot{\rho}_*(z) \, M_\odot \, yr^{-1} \, Mpc^{-3}$$  \hspace{1cm} (1)

The quantity $\mathcal{E}_{SNeIa}(z)$ (given in the fourth column of Table 1) is thus just the number of SNeIa per unit mass spent in forming stars at a given $z$, and it is independent from the cosmological model assumed. This efficiency reflects the evolutionary time scale (from birth to explosion) of the progenitor systems and the range of initial conditions leading to SNeIa explosions, together with other possible evolutionary effects (such as dependence on initial metallicity). The dependence on the time scale is illustrated in Figure 1 for the two main types of progenitor systems so far proposed, and for three different $\dot{\rho}_*(z)$. The systems labelled CLS(W) have evolutionary time scales of the order of a few Gyr whereas those labelled DD have time scales of the order of a few hundred million years only. The “flat” evolution of the efficiency for the DD systems for decreasing $z$ is due to the fact that $\mathcal{R}_{Ia}(z)$ closely follows $\dot{\rho}_*(z)$. Instead, $\mathcal{E}_{SNeIa}(z)$ significantly increases towards lower $z$ for the CLS(W) systems because the systems now exploding are a fixed fraction of the stars formed a few Gyr ago, when $\dot{\rho}_*(z)$ was higher. The flattening of $\mathcal{E}_{SNeIa}(z)$ at larger $z$
corresponds to a similar flattening of the $\dot{\rho}_* (z)$ considered. The absolute values of $\mathcal{E}_{\text{SNeIa}}(z)$ reflect the abundance of progenitor systems (and thus the range of initial conditions leading to SNeIa), and they will be discussed below.

The two types of systems whose $\mathcal{E}_{\text{SNeIa}}(z)$ is shown in Figure 1 have emerged in the last years as the main candidates to SNeIa progenitors. The DD systems are binaries made of a couple of CO WDs with a total mass exceeding the Chandrasekhar mass, and close enough to merge due to emission of gravitational waves in less than a Hubble time (Webbink 1984; Iben and Tutukov 1984). The CLS(W) systems consist of a CO WD plus a subgiant or red–giant companion that is overfilling its Roche lobe and transferring matter from its envelope to the WD (cataclysmic–like system or Algol–type binary that might be observed as a supersoft X–ray source). This scenario was originally proposed by Whelan & Iben (1973) and recently refined by Hachisu, Kato, & Nomoto (1996), who introduce the effects of a strong wind emitted by the accreting WD to stabilize mass transfer. That would allow the WD to reach the Chandrasekhar mass by steadily burning H into He and then He into CO (see also Nomoto, Iwamoto, & Kishimoto 1997). General discussions of the possible SNeIa progenitor systems can be found in Ruiz–Lapuente, Canal, & Burkert (1997).

The $\mathcal{E}_{\text{SNeIa}}(z)$ values in Table 1 are based on $\dot{\rho}_* = 2.01^{+0.18}_{-0.18} \times 10^{-2} h_{65} M_\odot Mpc^{-3} \text{yr}^{-1}$ (Gronwall 1999) for the local SFR. For higher $z$, we give the average of the values calculated for each of the three different $\dot{\rho}_* (z)$ referred to in Figure 1. The low–redshift efficiencies correspond to 1 SNeIa per $\sim 900 M_\odot$ going into star formation. As we see, $\mathcal{E}_{\text{SNeIa}}(z)$ is of the same order up to $z \sim 0.55$. Ongoing searches will soon yield the efficiency at $z \simeq 1$. If we assume that all stars with initial masses $M \gtrsim 10 M_\odot$ produce SNeII + SNeIb/c (gravitational–collapse SN), then $R_{\text{II+Ib/c}}(z) \simeq 0.0054 \times \dot{\rho}_*(z)$, for a Salpeter initial mass function (IMF) with $x = 1.35$, extending from 0.1 $M_\odot$ up to 100 $M_\odot$. With the above values, that gives about 5 gravitational–collapse SN for every SNeIa in the local Universe.
(see Table 1), in good agreement with the observations.

We can relate $\mathcal{E}_{\text{SNeIa}}(z)$ to the fraction $\eta$ of stars in the $3 \, M_\odot \lesssim M \lesssim 9 \, M_\odot$ initial mass range that should produce SNeIa if $\mathcal{R}_{\text{Ia}}(z)$ closely followed $\dot{\rho}_*(z)$, since we would then have:

$$
\mathcal{E}_{\text{SNeIa}}(z) = \eta \times \frac{\int_3^9 \Phi(M) \, dM}{\int_{0.1}^{100} M \, \Phi(M) \, dM}
$$

where $\Phi(M)$ is the IMF. For the same IMF as above, we would have $\mathcal{E}_{\text{SNeIa}}(z) = 0.02304 \times \eta$, which would mean $\eta \simeq 0.06$ for the $\langle \mathcal{E}_{\text{SNeIa}} \rangle$ given below. Some 6% of the stars in the above mass range (making the approximation that all stars were born in binaries) should thus give rise to SNeIa. Given the strong selection that any initial population of binaries with primaries in that mass range undergoes in any scenario, at different evolutionary steps, until becoming a SNeIa candidate, the figure looks high if there is no help from the fact that most systems now exploding were formed at an epoch when $\dot{\rho}_*(z)$ was considerably higher than at the redshifts considered here, and it confirms the impression carried by Figure 1 that the DD systems, with their short evolutionary timescales adding to the strong evolutionary constraints, do fail to account for the bulk of observed SNeIa. We will see in the next Section that modeling of the Galactic DD population reinforces this conclusion.

Comparing the measured $\mathcal{E}_{\text{SNeIa}}$ with that predicted from the DD scenario, at $z \simeq 0.55$ for instance, one sees that the prediction ($\mathcal{E}_{\text{SNeIa}} = 1.80 \times 10^{-4} \, M_\odot^{-1}$) is more than $2.95\sigma$ below the measurement ($\mathcal{E}_{\text{SNeIa}} = 1.42^{+0.45}_{-0.42} \times 10^{-3} \, M_\odot^{-1}$). The $\chi^2$ test gives a probability $P < 0.006$ that the two efficiencies were the same. Even allowing for a systematic error by a factor of 2 in the theoretical prediction of the rates and taking then the upper limit, the prediction would still be more than $2.5\sigma$ below the observational value ($P < 0.012$). If we refer to average values over the interval $0 \leq z \leq 0.55$, then we have, from observations, $\langle \mathcal{E}_{\text{SNeIa}} \rangle = 1.41^{+0.40}_{-0.31} \times 10^{-3} \, M_\odot^{-1}$ whereas the DD prediction is $2.17 \times 10^{-4} \, M_\odot^{-1}$, more than $3.8\sigma$ below ($P < 0.004$).
Precise enough measurements of $R_{Ia}(z)$ at $z \gtrsim 1$ would in turn test the prediction that at those redshifts the decrease in metallicity should inhibit the strong wind mechanism in the CLS(W) systems (Kobayashi et al. 1998). A decrease in $E_{SNeIa}(z)$ should be observed, even if SNeIa do not completely disappear thanks to the early metal enrichment of elliptical galaxies.

2.1. The local density of double degenerate binaries

The accuracy of model predictions of the SNeIa rates expected from the merging of two CO WDs (the DD scenario) cannot just be tested against the actually measured rates, since the observed SNeIa can arise from a different evolutionary pathway. Only predicted rates much in excess of the measured ones would prove the modeling wrong. Since we find the efficiency of SNeIa production in the DD scenario to be too low as compared with that observed, some extra test of the general binary evolution model is required. Such a test is provided by the measured space density of binary systems consisting of a pair of WDs (DD systems). In the DD scenario, a fraction of those systems (close CO WD pairs with a total mass exceeding the Chandrasekhar mass and close enough to merge in less than a Hubble time) would be the SNeIa progenitors.

From existing surveys, no clear SNeIa progenitor candidate has been found among the detected DD systems, but aside from the role played by not too well controlled selection effects, the fact does not automatically validate model predictions that the space density of possible progenitors should be low enough for them to have escaped detection up to now. A better test is provided by the comparison of model predictions with the sample of DD systems already detected, even if no SNeIa candidate has yet been found. We have thus calculated, with the same Monte Carlo scenario code used to predict the SNeIa rates for different evolutionary scenarios (see Ruiz–Lapuente, Canal, & Burkert 1997, for instance),
the numbers of different types of DD binaries (He WD + He WD, CO WD + He WD, and CO WD + CO WD) that would form at times following an instantaneous burst of star formation. The formation of WD + MS pairs is also followed. That is later convolved with a SFR appropriate for the Solar neighbourhood (constant rate, \(\sim 1 \, M_\odot \, yr^{-1}\) for the whole Galactic disk), which gives us the number density of DD systems existing at the present time. Since WD pairs older than \(\sim 10^8 \, yr\) should have cooled below detection limits, the local SFR history is not really important when comparing the model with the observations.

We find that the space density of WDs with ages below \(10^9 \, yr\) (which roughly corresponds to \(M_V \leq 12.75\)) should be \(\sim 2.5 \times 10^{-3} \, pc^{-3}\), which agrees well with the observational estimates of Liebert, Dahn, & Monet (1988) (\(\sim 3 \times 10^{-3} \, pc^{-3}\)).

In Table 2 (first line) we give the predicted fractions of close DD and close WD + MS pairs versus all WDs (single plus both wide and close pairs). We also give the fraction corresponding to the predicted SNeIa candidates. In the second line is shown the current birth rate of the three types of systems, and in the third one the numbers of systems with ages below \(10^8 \, yr\). In the calculations we have adopted a value of the common envelope parameter \(\alpha_{CE} = 1\). Our results compare well with the observed samples (Saffer, Livio, & Yungelson 1998; Maxted & Marsh 1999). The predicted DD period and mass distributions do also agree (see Figure 2), especially if we take into account the observational biases against detection of systems with very low mass primaries (taken here to be the brightest, and thus the more recently formed members of the DD systems), and of binaries with either the longest or the shortest periods. Therefore, our modeling of the possible DD progenitors of SNeIa can be considered as being tested against all the currently available observational data, and our conclusion as to the low efficiency of the DD scenario in producing possible SNeIa progenitors, as compared with the measurements of the cosmic evolution of the SNeIa rates, appears robust.
3. Discussion and conclusions

We have shown how, by using a cosmic approach, the topic of which stars end their
evolution as SNeIa can be enlightened. About 6% of the binary stars in the range \(3 - 9 \, M_\odot\)
end their lives as SNeIa. This fraction is unattainable from the merging of C+O WD pairs,
since only about 1% of binaries with masses in that range have a final total mass which
is above the Chandrasekhar mass. The high production efficiency of SNeIa out of the
star formation process found from \(z \sim 0\) to \(z \sim 0.5\) and beyond suggests that the single
degenerate scenario best explains Type Ia explosions.

The above conclusion can be avoided if

1. The star formation rate is underestimated by a factor of 6 even in the reconstructions
   from \(z \sim 0\) till \(z \sim 0.5\) which give the highest estimates, while the rate of SNeIa is not
   underestimated. This situation seems unlikely as it would imply that the real SFR history
   is inconsistent with a dozen of empirical determination using very different methods.
   In addition, such extremely high SFRs would be in conflict with all we know about
   extragalactic background light. More specifically, at \(z = 0.55\) there is just a discrepancy
   by a factor \(\lesssim 1.5\) among the SFRs in Figure 1. The bulk of DD systems merging at that \(z\)
   were formed at \(z \sim 0.62\), where the range of possible SFRs is not any broader.

2. We have overestimated by a factor of 6 the empirical rates of SNeIa from \(z \sim 0\) till
   \(z \sim 0.5\). The possibility of having overestimated the SNeIa rate is unlikely since critical
   aspects such as obscuration by dust, or undetectability of SNeIa near galactic nuclei, should
   produce the opposite effect.
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Table 1: Type Ia supernova rates and production efficiencies along z

| Redshift | \( \tau_{SNu} \) | \( R_{Ia} \) | \( \mathcal{E}_{SNeIa} \) | Probability |
|----------|----------------|-------------|-----------------|-------------|
| \( \langle z \rangle \) | SNu h\(_{65}^2\) | Mpc\(^{-3}\)yr\(^{-1}\)h\(_{65}^3\) | M\(_{-1}\)h\(_{65}^2\) | (\(\chi^2\) test) |
| 0.1      | 0.21\(^{+0.30}_{-0.13}\) | 2.2\(^{+3.4}_{-1.4}\) \(10^{-5}\) | 1.09\(^{+1.55}_{-0.64}\) \(10^{-3}\) ** |
| 0.2      | 0.16\(\pm0.05\) | — | — | — |
| 0.13     | 0.12\(^{+0.13}_{-0.08}\) | 1.7\(^{+1.9}_{-1.1}\) \(10^{-5}\) | 1.24\(^{+1.39}_{-0.81}\) \(10^{-3}\) *** |
| 0.32\(^4\) | < 0.32 (1\(\sigma\)) | < 4.52 (1\(\sigma\)) 11.02 (2\(\sigma\)) \(10^{-5}\) | < 2.27 – 5.54 \(10^{-3}\) *** |
|          |                    | < 6.2 (1\(\sigma\)) 15.0 (2\(\sigma\)) \(10^{-5}\) * |
| 0.38\(^5\) | 0.35\(^{+0.38}_{-0.26}\) | 4.8\(^{+3.3}_{-2.2}\) \(10^{-5}\) | 2.20\(^{+1.51}_{-1.01}\) \(10^{-3}\) *** |
|          |                    | 6.9\(^{+4.8}_{-3.2}\) \(10^{-5}\) * |
| 0.55\(^6\) | 0.26\(\pm0.08\) | 4.53\(^{+1.43}_{-1.35}\) \(10^{-5}\) | 1.42\(^{+0.45}_{-0.42}\) \(10^{-3}\) *** |
|          |                    | 6.74\(^{+2.13}_{-2.00}\) \(10^{-5}\) * |

\(P < 0.004\)

\(^1\)Hamuy & Pinto (1999); \(^2\)Cappellaro et al. (1997); \(^3\)Hardin et al. (1999); \(^4\)Hamilton (1999);
\(^5\)Pain et al.(1996); \(^6\)Pain et al.(2000) *For the cosmology \(\Omega_M = 0.3\) \(\Omega_A = 0.0\); **SFR from Gronwall (1999); ***Averaging over the SFRs used in Figure 1;
Table 2: Predicted fractions of DDs and of WD + MS pairs

|        | Close DD | CO + CO | Pre–SNeIa | CO + He | He + He | Close WD + MS |
|--------|----------|---------|-----------|---------|---------|---------------|
| 1/15   | 1/114    | 1/419   | 1/24      | 1/58    | 1/6     |
| 0.056  | 0.008    | 0.002   | 0.037     | 0.011   | 0.146   |
| 5.6×10^6 | 8.5×10^5 | 2.2×10^5 | 3.7×10^6  | 1.1×10^6 | 1.5×10^7 |
Fig. 1.— Model predictions of $\mathcal{E}_{\text{SNeIa}}$, the “efficiency” in producing SNeIa, that is the number of SN per unit mass of stars being formed, at a given $z$. The curves show its expected evolution for two SNeIa candidates systems with different timescales to explosion: merging of two CO WDs (dashed line, labelled DD), and cataclysmic–like binaries (or Algol–type systems), with the stabilizing effects of the accretion–induced wind included (solid line, labelled CLS(W), see text for further explanation). The results for three different star–formation histories are shown: Madau et al. (1998), Steidel et al. (1998), and Blain et al. (1998). The data points come from the SNeIa rate measurements of Pain et al. (1996, 2000), Hardin et al. (1999), and Hamuy & Pinto (1999). The results are independent from the cosmological model adopted. Note that the vertical scale of the first panel is different from the other two.
Fig. 2.— *Top panel*: Expected mass distribution of the brightest components of DD systems (solid histogram). The dot–dashed histogram shows the distribution in the observed sample. *Bottom panel*: Expected period distribution of DD systems (solid histogram). The dot–dashed histogram shows the distribution in the observed sample. The scarcity of low–mass WDs in the observed sample, as compared with the model prediction, can be explained by the increasing difficulty in detecting lower mass WDs, and the same applies to either very short or very long periods.