POPULATION SYNTHESIS FOR PROGENITORS of TYPE IA SUPERNOVAE
Lev R. Yungelson
Institute of Astronomy of the Russian Academy of Sciences

Abstract

We discuss application of population synthesis for binary stars to progenitors of SN Ia. We show that the only candidate systems able to support the rate of SNe Ia $\nu_{\text{Ia}} \sim 10^{-3} \text{yr}^{-1}$ both in old and young populations are merging white dwarfs. In young populations ($\sim 1 \text{Gyr}$) edge-lit detonations in semidetached systems with nondegenerate helium star donors are also able to support a similar $\nu_{\text{Ia}}$. The estimated current Galactic rate of SN Ia with single-degenerate progenitors is $\sim 10^{-4} \text{yr}^{-1}$.

1 Introduction

There is little doubt that explosions of SN Ia are thermonuclear disruptions of the mass-accreting carbon-oxygen white dwarfs (CO WD) in binaries. The main facts arguing for this are: released energy per 1 g is comparable to $\epsilon_{\text{CO} \rightarrow \text{Fe}}$; explosive nature of the events suggests that degeneracy plays a significant role; explosions may occur long after cessation of star formation; hydrogen is not detected in the spectra of SN Ia (but see discussion of single-degenerate scenario below).

Identification of the SN Ia progenitors is important for several reasons. It may help to constrain the theory of binary–star evolution. Modeling and understanding the explosions requires knowledge of the initial conditions for them and the environments in which they take place. Evolution of the galaxies depends on the radiative, kinetic energy, and nucleosynthetic output of SN Ia and the evolution of SN Ia rate in time, which, in turn, depend on the nature of the progenitor systems. The nature of the progenitors is related to the use of SN Ia as distance indicators for determination of cosmological parameters $H_0$ and $q_0$.

Evolution of the luminosity function and the rate of SNe is important in this respect.

A successful model for the population of progenitors of SN Ia has to explain the inferred Galactic rate of events $(4 \pm 2) \cdot 10^{-3} \text{yr}^{-1}$ (Cappellaro & Turatto [2001]), the origin of the observational diversity among local ($z < 0.1$) SNe Ia $- 36 \pm 9\%$ may be “peculiar” [Li et al. 2001], and the occurrence of SNe Ia in stellar populations having a wide range of ages.

Below, we discuss the scenarios of formation of binary systems in which SN Ia may occur and the rate of SN Ia, $\nu_{\text{Ia}}$, predicted by different scenarios.

2 Population synthesis

The data provided by stellar evolution theory allows to construct numerical evolutionary scenario that describes the sequence of transformations of a binary system with given initial masses of components and their separation ($M_{10}, M_{20}, a_0$) that it can experience in its lifetime.

Statistical studies of stars provide information on the binarity rate and the distributions of binaries over $M_{10}$, $a_0$, $q_0 = M_{20}/M_{10}$. Combined with star
formation history, this allows to estimate the birthrate of the systems with a given set of \((M_{10}, M_{20}, a_0)\) at any epoch. Then, it is possible to compute their contribution to the past or present population of stars of different types. Integration over whole space of initial parameters or Monte Carlo simulation for a large sample of initial “binaries” gives a complete model of the population of binaries and occurrence rates of different events, e. g., SN. Objects of the same type may be formed by several routes, hence, one may expect variations of SN Ia.

Figure 1: Evolutionary scenarios for possible progenitors of SN Ia.
Table 1: Occurrence rates of SNe Ia in candidate progenitor systems (in yr\(^{-1}\))

| Donor        | CO WD | MS/SG | He star | He WD | RG |
|--------------|-------|-------|---------|-------|----|
| Counterpart  | Close | Supersoft | Blue | AM CVn | Symbiotic |
| Binary WD   | XRS   | sd    | Star   |       |     |
| Mass transfer mode | Merger | RLOF | RLOF | RLOF | Wind |
| Young population | \(10^{-3}\) | \(10^{-4}\) | \(10^{-4}\) | \(10^{-5}\) | \(10^{-6}\) |
| Old population | \(10^{-3}\) | – | – | \(10^{-5}\) | \(10^{-6}\) |
| Young population | – | \(\lesssim 10^{-4}\) | \(10^{-3}\) | – | \(\lesssim 10^{-3}\) |

3 Evolutionary scenarios for progenitors of SN Ia

Figure 1 shows (not to scale) a simplified flowchart of the main scenarios in which one may expect formation of a progenitor of SN Ia – a CO WD that may ignite carbon in the center. The rates of formation of potential SN Ia via different channels are summarized in Table 1.

**Scenario A** ["double-degenerate"– DD – scenario, (Tutukov & Yungelson 1981; Webbink 1984; Iben & Tutukov 1984)] starts with a main-sequence (MS) binary with \(M_1 \sim (4-10) M_\odot\). The system is wide enough for Roche-lobe overflow (RLOF) to occur when the primary is an AGB star with a degenerate CO core. After RLOF, a common envelope (CE) forms. If components do not merge inside CE, the core of the primary becomes a CO WD. After dispersal of CE, the system remains wide enough for the secondary to become a CO WD too. The angular momentum loss (AML) via gravitational waves radiation (GWR) results in the RLOF by the lighter of two WD. Mass loss proceeds on dynamical time scale and in several orbital revolutions Roche-lobe filling WD turns into a disk around the more massive WD (Tutukov & Yungelson 1979; Benz et al. 1990). If the total mass of the system exceeds \(M_{\text{Ch}}\), accretion from the disk may result in accumulation of \(M_{\text{Ch}}\) by the “core” and SN Ia.

**Scenario B** is realized in the systems with \(M_{20} \lesssim 2.5 M_\odot\) and such a separation of components after formation of the first WD that the secondary fills its Roche lobe in the hydrogen-shell burning stage and becomes a helium WD. Like in scenario A, dwarfs are brought into contact by the AML via GWR. Unstable merger, most likely, results either in ignition of He at the interface of accretor and disk (Ergma et al. 2001), formation of a CE and loss of He-rich matter or in formation of an R CrB-type star (Webbink 1984; Iben et al. 1996). If a stable semidetached system (of an AM CVn-type) forms, accumulation of \(M_{\text{Ch}}\) by accretor becomes possible.

In scenario **Scenario C** ["edge-lit detonation" – ELD – scenario, (Livne 1990)] \(2.5 \lesssim M_{20}/M_\odot \lesssim 5\) and the separation between components after the first CE phase is such that the secondary fills its Roche lobe before core He ignition and becomes a low-mass \(\sim (0.35 - 0.8) M_\odot\) compact He-star. Low-mass helium remnants of stars have lifetime comparable to the MS-lifetime of their progenitors. This allows AML via GWR to bring He-stars to RLOF before exhaustion of He in the cores. If mass loss occurs stably, \(\dot{M}_a \sim (2 - 3) \cdot 10^{-8} M_\odot\) yr\(^{-1}\), almost independent of the mass of companion (Savonije et al. 1986; Tutukov & Fedorova 1989). Under such \(\dot{M}_a\) a degenerate He-layer forms
atop WD and detonates when its mass increases to $\sim 0.1 \, M_\odot$ \cite{limongi1991}. Detonation of He produces an inward propagating pressure wave that leads to close-to-center detonation of C. The total mass of configuration in this case may be sub-Chandrasekhar.

**Scenario D** [“single degenerate” – SD – scenario, \cite{whelan1973}] occurs in the systems where low-mass MS (or close to MS) stars [$M_{20} \lesssim (2 - 3) \, M_\odot$] or (sub)giant ($M_{20}/M_1 \lesssim 0.8$) companions to WD stably overflow Roche lobes. Accreted hydrogen burns into helium and then into CO-mixture. This allows to accumulate $M_{\text{Ch}}$.

**Scenario E** is the only way to produce SN Ia in a wide system, via accumulation of a He layer for ELD or $M_{\text{Ch}}$ by accretion of stellar wind matter in a symbiotic binary \cite{tutukov1976}.

Scenarios A – E are associated with binaries of different types and with different masses of components. This sets an “evolutionary clock” – the time delay between formation of a binary and SN Ia. Figure 2 shows the differential rates of SN Ia produced via channels A, C, and D after a burst of star formation. The DD-scenario is the only one that may operate in the populations of any age, while SD- or ELD-scenarios are not effective if star formation ceased several Gyr ago.

Table 1 presents the order of magnitude model estimates for $\nu_{\text{Ia}}$ after 10 Gyr since beginning of star formation in the populations that have similar total mass comparable to the mass of the Galactic disk. Computations were made by the code used, e. g., by Tutukov and Yungelson \cite{tutukov1994} and Yungelson and Livio.
(1998) for the value of common envelope parameter $\alpha_{ce} = 1$. Differences in assumptions in population synthesis codes or parameters of computations result in numbers that vary by a factor of several; this is the reason for giving only order of magnitude estimates). "Young" population had constant star formation rate for 10 Gyr; in the "old" one the same amount of gas was converted into stars in 1 Gyr. We also list in the table the types of observed systems associated with certain channel and the mode of mass transfer. Like Fig. 2, table 1 shows that, say, for elliptical galaxies where star formation occurred in a burst, DD-scenario is the only one able to respond for occurrence of SN Ia, while in giant disk galaxies with continuing star formation another scenarios may contribute as well.

For a certain time the apparent absence of observed DD with $M_{\text{tot}} \geq M_{\text{Ch}}$ merging in Hubble time was considered as the major "observational" difficulty for scenario A. Theoretical models predicted that it may be necessary to investigate for binarity up to 1000 field WD with $V \lesssim 16 \div 17$ for finding a proper candidate [Nelemans et al. 2001]. The "necessary" number of WD was studied within SPY-project [Napiwotzki et al. 2001] and resulted in discovery of the first super-Chandrasekhar pair of dwarfs [R. Napiwotzki (this volume), Napiwotzki et al., (2003)].

On the "theoretical" side, it was shown for one-dimensional non-rotating models that the central C-ignition and SN Ia explosion are possible only for $\dot{M}_a \lesssim (0.1 - 0.2) \dot{M}_{\text{Edd}}$ [Nomoto & Iben 1985]. But it was expected that in the merger products of binary dwarfs $\dot{M}_a$ is close to $\dot{M}_{\text{Edd}} \sim 10^{-5} \, M_\odot \, \text{yr}^{-1}$ [Mochkovitch & Livid 1990] because of high viscosity in the transition layer between the core and the disk. For such $\dot{M}_a$ the nuclear burning will start at the core edge, propagate inward and convert the dwarf into an ONeMg one. The latter will collapse without SN Ia [Isern et al. 1983]. However, consideration of the role of deposition of angular momentum into central object (Piersanti et al., 2003a,b) has shown that, as a result of spin-up of rotation of WD, instabilities associated with rotation, deformation of WD and angular momentum loss by distorted configuration via GWR, $\dot{M}_a$ that is initially $\sim 10^{-5} \, M_\odot \, \text{yr}^{-1}$, decreases to $\sim 4 \cdot 10^{-7} \, M_\odot \, \text{yr}^{-1}$. For this $\dot{M}_a$ close-to-center ignition of carbon becomes possible.

Because of long apparent absence of an observed “loaded gun” for the DD-scenario and its “theoretical problems”, SD-scenario (D) is often considered as the most promising one. However, it also encounters severe problems. No hydrogen is observed in the spectra of SN Ia, while it is expected that $\sim 0.15 \, M_\odot$ of H-rich matter may be stripped from the companion by the SN shell [Marietta et al. 2000]. Hydrogen may be discovered both in very early and late optical spectra of SN and in radio- and X-ray ranges [Eck et al. 1995; Marietta et al. 2000; Lentz et al. 2002]. As well, no expected (Marietta et al. 2001; Podsiadlowski 2003) high luminosity and/or high velocity former companions to exploding WD were discovered as yet.

In the SD-scenario, hydrogen first burns into helium and then into C/O mixture. However, two circumstances hamper accumulation of $M_{\text{Ch}}$.

At $\dot{M}_a \lesssim 10^{-8} \, M_\odot \, \text{yr}^{-1}$ all accumulated mass is lost in Nova explosions [Prialnik & Kovetz 1995]. Even if $\dot{M}_a$ allows accumulation of He-layer, most of the latter is lost

---

1Recently discovered SN Ia 2001ic and similar 1997cy [Hamuy et al. 2003] may belong to the so-called SN 1.5 type or occur in a symbiotic system [Chugai & Yangelson 2004].
after He-flash (Iben & Tutukov 1996; Cassisi et al. 1998; Piersanti et al. 1999), dynamically or via frictional interaction of binary components with giant-size CE. Thus, the results of computations strongly depend on the assumptions on the amount of mass loss in the nuclear-burning flashes. The flashes become less violent and more effective accumulation of matter may occur if mass is transferred on the rate close to the thermal one (Iben & Tutukov 1984; Yungelson & Livio 1998; Ivanova & Taam 2003). However, this assumption seems to lead to overproduction of supersoft X-ray sources [see the estimate of the number of sources in Fedorova et al. (2004) and completeness of surveys estimates in Di Stefano & Rappaport (1997)].

The “favorable” range of mass transfer rates widens if mass exchange is stabilized by optically thick stellar wind from WD (Hachisu et al. 1996). Under this assumption (not based on a rigorous treatment of the radiation transfer), the excess of transferred matter over the upper limit for stable hydrogen burning ($\simeq 5 \cdot 10^{-7} M_{\odot} \text{ yr}^{-1}$ for a $1 M_{\odot}$ WD) is blown out of the system taking away specific angular momentum of the WD. This allows to avoid formation of CE for mass transfer rates up to $\simeq 10^{-4} M_{\odot} \text{ yr}^{-1}$ and, simultaneously, implies stable hydrogen burning and reduces mass loss in helium burning flashes. Figure 2 shows the range of masses of donors and accretors in “successive” SN Ia progenitors at the beginning of accretion onto the WD stage, obtained under “stabilization” condition and for thermal-time scale mass transfer by Fedorova et al. (2004). The maximum of $\nu_{\text{Ia}}$ in the latter study is $2 \cdot 10^{-4} \text{ yr}^{-1}$, i. e., it still does not exceed $\sim 10\%$ of the inferred Galactic $\nu_{\text{Ia}}$. Han & Podsiadlowski (this volume) obtain for this channel the rate up to $1.1 \cdot 10^{-3} \text{ yr}^{-1}$, closer to the observational estimate.

An important source for discrepant $\nu_{\text{Ia}}$ obtained for SD-scenario may be the
difference in the assumptions on the mass accumulation efficiency. As an extreme example, the upper panel of Fig. 4 shows the efficiency of accumulation of He and C+O if one takes into account stellar wind mass loss by dwarfs that burn hydrogen steadily, mass loss in Novae explosions after Prialnik and Kovetz (1995) and estimates of mass loss in helium flashes after Iben and Tutukov (1996); the lower panel shows efficiency of accumulation under prescriptions adapted by Han & Podsiadlowski [Fedorova et al. (2004) implemented an “intermediate” case: assumptions on H-accumulation after Prialnik and Kovetz and assumptions on He-burning similar to Han & Podsiadlowski].

Scenario C may operate in populations where star formation have ceased no more than \( \sim 1 \) Gyr ago and produce SN at the rates that are comparable with the Galactic \( \nu _{\text{Ia}} \). But the outcome of ELD currently seems to be not compatible with observations of SN Ia. “By construction” of the model, the most rapidly moving products of explosions have to be He and Ni; this is not observed. The spectra produced by ELD are not compatible with observations of the overwhelming majority of SN Ia (Hoeflich et al 1996). On the theoretical side, it is possible that lifting effect of rotation that reduces effective gravity and degeneracy in the helium layer may prevent detonation (Langer et al 2003).

Channel B most probably gives a very minor contribution to the total SN Ia rate since typical total masses of the systems are well below \( M_{\text{Ch}} \).

The peculiarity of channel E is the behavior of \( \dot{M}_a \) from the wind: it is initially very low and grows, as companion to the WD expands. Typical initial masses of WD in symbiotic stars are well below \( 1 M_\odot \) (Yungelson et al. 1995). For them it is more likely to accumulate a helium layer that may be lost in a thermal flash than accumulate \( M_{\text{Ch}} \).
4 Conclusion

1. Only DD may secure the observed $\nu_{\text{Ia}}$ both in old and young populations. Merging pairs with $M_1 + M_2 \simeq M_{\text{Ch}}$ were discovered after search in a WD-sample of appropriate size. Account for effects of rotation may solve the problem of central ignition in the merger product. Crucially needed is a study of the physics of merger which follows development of shocks and turbulence in the “transition” zone, transfer of momentum, rotation effects upon evolution of the “core-disk” configuration.

2. Edge-lit detonations in He-accreting systems can be responsible for SN Ia-scale events only in the populations younger than $\sim 1$ Gyr. Lifting effect of rotation may reduce the number and scale of ELD.

3. Single-degenerate scenario may contribute a fraction ($\sim 10\%$) of all events in young or intermediate age populations. The major obstacle to SD-scenario are H and He thermal flashes. Predictions of the rate of SD-events have to be reconciled with the number of supersoft X-ray sources. A crucial test for SD-scenario would be detection of H which may be present due to the interaction of SN shell with companion or a “slow wind” of pre-SN.

4. In the DD-scenario one may expect that exploding objects would differ in mass and central C-abundance. In SD-scenario all exploding WD most probably have $M_{\text{Ch}}$, but differ in central C. It is unclear whether these differences may explain the diversity of observed SN Ia.

This study was supported by RFBR grant 03-02-16254 and Federal Program “Astronomy”. The author acknowledges financial support of IAU and JD5 SOC that enabled his participation in the meeting.

References

Benz, W., Bowers, R. L., Cameron, A. G., & Press, W. H. 1990, ApJ, 348, 647
Canal, R., Méndez, J., & Ruiz-Lapuente, P. 2001, ApJ, 550, L53
Cappellaro, E. & Turatto, M. 2001, in ASSL Vol. 264: The Influence of Binaries on Stellar Population Studies, 199
Cassisi, S., Iben, I. J., & Tornambe, A. 1998, ApJ, 496, 376
Chugai, N. & Yungelson, L. 2004, ALet, 30, 83, astro-ph/0308297
Di Stefano, R. & Rappaport, S. 1995, in ASP Conf. Ser. 72: Millisecond Pulsars. A Decade of Surprise, 155
Eck, C. R., Cowan, J. J., Roberts, D. A., Boffi, F. R., & Branch, D. 1995, ApJ, 451, L53
Ergma, E., Fedorova, A. V., & Yungelson, L. R. 2001, A&A, 376, L9
Fedorova, A. V., Tutukov, A. V., & Yungelson, L. R. 2004, ALet, 30, 73, astro-ph/0309052
Hachisu, I., Kato, M., & Nomoto, K. 1996, ApJ, 470, L97
Tutukov, A. V. & Yungelson, L. R. 1976, Astrofizika, 12, 521
Tutukov, A. V. & Yungelson, L. R. 1979, Acta Astron., 29, 665
—. 1981, Nauchn. Informatsii, 49, 3
—. 1994, MNRAS, 268, 871
Webbink, R. F. 1984, ApJ, 277, 355
Whelan, J. & Iben, I. J. 1973, ApJ, 186, 1007
Yungelson, L., Livio, M., Tutukov, A., & Kenyon, S. J. 1995, ApJ, 447, 656
Yungelson, L. R. & Livio, M. 1998, ApJ, 497, 168