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On the progenitors of type Ia Supernovae

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A chiunque custodisca la passione e la curiosità nel ricercare,
lo stupore nello scoprire e nel comprendere

Abstract

This work addresses to the question about type Ia supernova (SN Ia) progenitors.
A short but comprehensive review of the main results proposed in literature for the SN Ia candidate progenitors problem is here presented from both theoretical and observational points of view.
From the occurrence of SNe Ia in all type galaxies (hence the evidence of low-mass long-lived progenitors), the presence of a white dwarf (WD) is common to all the models.
Given the fact that the class of SNe Ia usually shows standard features, the most accredited scenario is that SN Ia explosion arises from a WD which accretes mass in a binary system reaching the uniform limit value of Chandrasekhar mass ($M_{Ch} \sim 1.39 M_{\odot}$).
These models are called "Chandrasekhar models" (the WD has to reach the Chandrasekhar mass to explode as SN Ia). Within this class two different kinds of models can be distinguished:

- Single-Degenerate (SD) model, in which the WD accretes mass from a non degenerate companion star.
  Besides the evidence of different candidates, the detection of this class of systems seems to be possible through the analysis of supersoft X-ray radiation, in addition to the possibility of hunting the companion star after the explosion.

- Double-Degenerate (DD) model, in which the accretion up to explosion is the result of a merging between two WDs.
  In addition to the theoretical problem of avoiding accretion induced collapse, also this class of models shows several candidates which in principle may be detected through the gravitational waves emission (even if it still remains a theoretical prediction).

Besides this group of models, another class is based on the assumption that the explosion of the WD as SN Ia takes place before it reaches the limit value (they correspond to the "sub-Chandrasekhar models"): the accreted matter from a He-rich donor star feeds mainly the SD channel while for the DD channel there is again the merging between two WDs with a total mass now lower than the Chandrasekhar limit. Even if these latter models are able to better explain the SN Ia rate, there is no physical evidence of their occurrence in nature and so they are disfavoured.
Observational hints for super-Chandrasekhar explosions are instead presently supporting the key role of rotation to exceed the limit mass.
Since there is no reason to consider SD and DD channels as mutually exclusive, in calculations of SN Ia rates both of them are usually taken into account, but the comparison with the observed SN Ia rate shows that there is no remarkable difference from the rates in which the two models are considered separately, hence no definitive conclusion can be drawn.
An alternative binary model is the Core-Degenerate channel, in which the WD merges with the massive core of an AGB star. It differs from the DD model mainly for the emission of magneto-dipole radiation (rather than gravitational waves) during the merging process. It seems to overcome some difficulties of the DD model, but it has to be investigated further.
A last alternative has been proposed recently and it indicates the possibility that a single WD can explode due to the energy produced by the pycnonuclear reactions triggered by the presence of impurities of light elements (hydrogen and helium).
This hypothesis has been so far explored with a semi-analytic treatment, so that a more physically consistent approach is required before concluding about its potential in the context of SN Ia candidates.

Contents

Chapter 1

Introduction

Supernovae represent the last stage of stellar evolution. A supernova is a star which undergoes a tremendous explosion or sudden brightening. During this time its luminosity becomes comparable to that of the entire galaxy (which can be made of 10^{11} stars).

1.1 The discovery of supernovae

Changes in the appearance of the night sky, visible with the naked eye, have always called for explanation. But, although "new stars" (i.e. novae and supernovae) have been observed by humans for thousand of years, the modern era of supernova research began only about a century ago. When the astronomical distance scale was not yet firmly established, both novae and supernovae were thought to be associated with the same explosion phenomenon, generically called "nova" (or "stella nova"). On 31 August 1885, the German astronomer Ernst Hartwig discovered and then analyzed a "nova", *S Andromedae*, near the center of the Andromeda galaxy (M31), which became invisible about 18 months later. In 1919 Lundmark estimated the distance of M31 to be about $d = 7 \cdot 10^5$ lyear. The fact of placing M31 outside the Milky Way at an incredible distance showed that the Hartwig's nova had a huge intrinsic luminosity: it was 1000 brighter than a normal nova. For this reason Lundmark and Curtis in the early 1920s were the first to talk about "giant novae". A similar event as *S Andromedae* was observed in 1895 in NGC 5253 ("nova" *Z Centaury*), and this time the "new star" appeared to be five times brighter than the entire galaxy. Soon, it was clear that two different classes of "stellae novae" existed, the most luminous ones corresponding to what today are called supernovae. Only in 1934 a clear distinction between novae and supernovae was made [Baade and Zwicky, 1934a]. In the following years, systematic searches leaded to the discovery of numerous supernovae and analyses of the spectral features of these objects led to the comprehension of their intrinsic characteristics. ([Hillebrandt and Niemeyer, 2000], [José et al., 2011]).

1.2 Classification of supernovae

Supernovae (SNe) can be grouped in different types; the main features to distinguish them is the presence or the absence of hydrogen (H) in the observed spectrum:

- Type I SNe are characterized by the lack of H in the spectrum;
- Type II SNe are characterized by the presence of H in the spectrum.

1.2.1 Type I SNe

Type I SNe can be further sub-grouped:

- *Type Ia SNe*:
  This group was introduced by R. Minkowsky and F. Zwicky. These SNe are characterized by the presence of strong silicon (Si II) lines around maximum brightness, and by the presence of Fe e Co lines after several months. They occur in galaxies of all types, including in the elliptical ones (which are made of old stellar populations). This indicates that SNe Ia can have long-lived, low mass progenitors. They are commonly thought to originate from a white dwarf (WD) which accretes material in a binary system.
  About $25 - 30\%$ of observed supernovae are SNe Ia. They are, on average, the most luminous of all supernova types, and their lightcurves form a homogeneous group;

- *Type Ib SNe*:
  They are characterized by the presence of strong He lines in their spectra, and by lines of O, Ca and Mg. They are commonly thought to originate from supergiants which have had their outer H layers removed. They are found in star-forming regions, such as in the gas rich and dust rich arms of spiral galaxies;

- *Type Ic SNe*: They are characterized by the absence of He lines in the spectra, and by the presence of O, Ca and Mg lines. They are thought to originate from supergiants which have had their outer H and He layers removed. They are found in star-forming regions.
  A subclass of SNe Ic are known as hypernovae: they are very bright and they may be associated with gamma-ray bursts. Together with the SNe Ib they constitute about 20% of all supernovae.

1.2.2 Type II SNe

The spectra of SNe II are dominated by the presence of H lines, while the lines of Ca, O and Mg are also present. As the SNe Ib and Ic, they occur in the spiral arms of galaxies where star formation takes place and young stars are abundant, and therefore they correspond to the explosions of massive stars with short lifetimes. They are about 50% of all supernovae. In several cases, the progenitors of Type II supernovae have been detected before explosion. These progenitors are red supergiants with masses $8M_{\odot} \leq M \leq 16M_{\odot}$. SNe II are often sub-classified into Type II-P (showing, after the peak in brightness, a long 'plateau' phase of 2-3 months before a slow exponential decay), and Type II-L (with the lack of plateau phase). They finally can be distinguished in Type IIb (in which the spectral signatures change from Type IIb to Type Ib), and Type IIn (showing narrow emission lines on top of broad emission lines, interpreted as resulting from heavy mass loss prior to the explosion).

Summarizing, SNe Ib, SNe Ic, SNe II originate from the core collapse of evolved massive stars (they are also called "core-collapse supernovae") and the dynamics of these explosion processes are well studied and accepted. These SNe are not observed in old stellar populations (such as in elliptical galaxies). On the other hand, SNe Ia originate from the thermonuclear explosion of low-mass stars (i.e. CO-WDs that reach a critical mass for carbon ignition), but the progenitor models such as the dynamics of the explosion mechanism are still controversial. SNe Ia, compared to the other types of SNe, are found in all types of galaxies (also in the elliptical ones), as the graphic [1.1] shows.

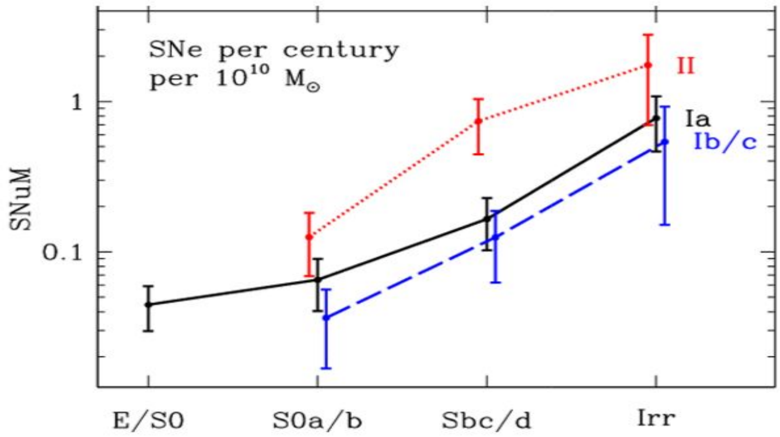


Figure 1.1: SNe per century per $10^{10} M_{\odot}$ is plotted as a function of galaxies of different types; only SNe Ia are found in old stellar populations.

1.3 Type Ia SNe: homogeneity and differences

The presence of some difference can be found also within the group of Type Ia supernovae: nearly 70% of all SNe Ia form a homogeneus class in terms of their spectra, lightcurve and peak luminosity. These SNe Ia are called "normals" (or "Branch normals"). The remnant 30% of SNe Ia is made of particular events which deviate from the classical features: there are sub-luminous events (related to the weakest events in terms of explosion strenght) and super-luminous events (related to events stronger than normal ones).

1.3.1 Main features of normal SNe Ia

The classification of SNe Ia is based on spectroscopic features: the absence of H absorption lines, which distinguish them from SNe II, and the presence of strong Si II lines in the early and maximum spectrum ($\lambda = 6355$Å shifted to 6100Å), which classified them as SNe Ia [Wheeler and Harkness, 1990]. The spectra, light curves and peak absolute magnitudes of normal SNe Ia are homogeneus: a normal SN Ia rises to maximum light in a period of 20 days [Riess et al., 1999] reaching

$$M_V \approx M_B \approx -19.30 \pm 0.03 + 5\log(\frac{H_0}{60}) \tag{1.1}$$

with a dispersion of $\sigma(M_V) \approx \sigma(M_B) \approx 0.2 - 0.3$ ([Hamuy et al., 1996], [Tammann and Sandage, 1995]), then it is followed by a rapid decline of about three magnitudes in 1 month, approximately, and later the light curve tail falls off in an exponential manner at a rate of one magnitude per month. The shape of normal SNe Ia light-curve compared to the one of other SNe is shown in fig. [1.2]

The optical spectra of normal SNe Ia contain neutral and singly ionized lines of Si, Ca, Mg, S and O at maximum light, indicating that the outer layers of the ejecta are mainly composed of intermediate mass elements [Filippenko, 1997]. Permitted Fe II lines dominate the spectra roughly 2 weeks after maximum, when the photosphere begins to penetrate Fe-rich ejecta [Swartz et al., 1991]. In the nebular phase of the light curve tail, beginning approximately 1 month after peak brightness, forbidden Fe II, Fe III, and Co III lines become the dominant spectral features [Axelrod, 1980]. The decrease of Co lines and the relative

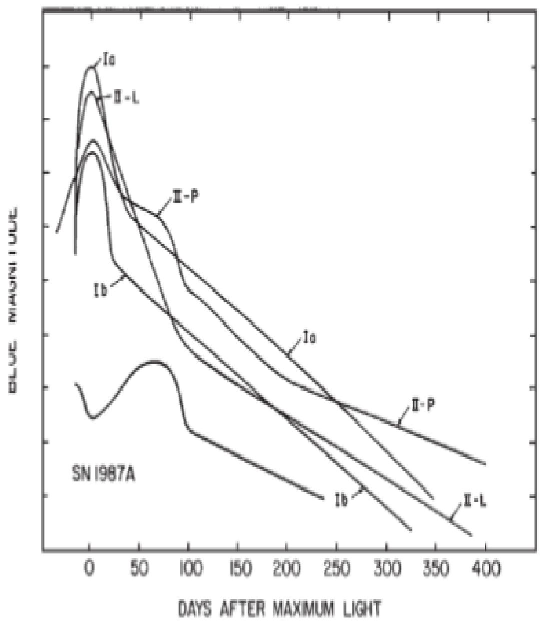


Figure 1.2: Normal SN Ia light-curve compared to the one of other SNe: variation of B-band magnitude with time [Filippenko, 1997]

intensity of Co III and Fe III [Kuchner et al., 1994] give evidence that the light curve tail is powered by radioactive decay of ^{56}Co ([Truran et al., 1967], [Colgate and McKee, 1969]). ([Hillebrandt and Niemeyer, 2000], [Livio, 2013]).

1.3.2 Particular events

Apart from the 70% of normal events, in the class of heterogeneous SNe Ia there are about 9% over-luminous events (called SN1991T-like events), 18% sub-luminous events (called SN1991bg-like events) and 3% of SN2002cx-like events ([Li et al., 2003], [Li et al., 2011b]).

Therefore a model which proposes to examine or explain the SN Ia explosion mechanism, such as the progenitor configuration, must take into account the diversity within this class of objects that are associated to the same physical phenomenon.

1.4 Pre-evolution of a WD and its physical properties

Since the fact that in the progenitor systems of SNe Ia the presence of a WD is well accepted, it is important to consider the main physical features of these stars in order to better understand the conditions at the SN Ia generation.

About 97% of the stars with lifetime shorter than the age of Universe end as WDs. The range of WD masses extends from about $0.4M_{\odot}$ to $1.2 - 1.3M_{\odot}$; the peak value is $0.6M_{\odot}$. This fate is common among low- and intermediate-mass stars with initial masses in the range $0.9M_{\odot} \leq M \leq 6 - 9M_{\odot}$. WDs have characteristic radii of about $5000km$ and mean densities of around $10^6 g \cdot cm^{-3}$. These stars no longer burn nuclear fuel but they are slowly cooling as they radiate away their residual thermal energy. Their compact nature was first confirmed by Adams [Adams, 1925] and Eddington [Eddington and Eddington, 1926]. In

December 1926 R. H. Fowler [Fowler, 1926] applied Fermi-Dirac statistics to explain the nature of WDs: he identified that these stars are held up from gravitational collapse by electron degeneracy pressure.

1.4.1 WD and electron degeneracy

Electrons are fermions that obey the Pauli's exclusion principle (no two fermions can exist in identical energy quantum state) and are described by the Fermi-Dirac distribution:

$$f_{FD}(E) = \frac{1}{\exp\left(\eta + \frac{E}{kT}\right) + 1} \leq 1 \tag{1.2}$$

(with η that is the degeneration parameter). Given the number density $n(E) = g(E)f_{FD}(E)$, (with $g(E)$ the density of states), its maximum value is obtained setting $f_{FD}(E) = 1$. It can be seen that, if the classical particles are well described by the Maxwell-Boltzmann distribution (which does not impose any restriction about the number of electrons), for low values of temperature this kind of distribution invades the forbidden region set by the $n_{max}(E)$ (i.e. the maximum number density of fermions which respect the Pauli' exclusion principle): Maxwell-Boltzmann distribution is not a good approximation.

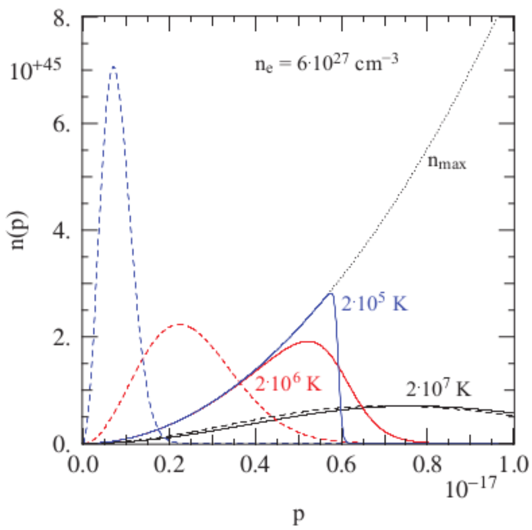


Figure 1.3: Electron momentum distribution $n(p)$ as function of the momentum p for different values of the temperature: $T = 2 \cdot 10^7 K$ (black lines), $T = 2 \cdot 10^6 K$ (red lines), $T = 2 \cdot 10^5 K$ (blue lines). The actual distributions, governed by quantum mechanics, are shown as solid lines while the Maxwell-Boltzmann distributions for the same n_e and T values are shown as dashed lines. The dotted line n_{max} is the maximum possible number distribution if all quantum states with momentum p are fully occupied.

Due to Pauli's exclusion principle, electrons can exert a higher pressure than expected by classical physics: degeneracy pressure. Therefore, at electron number density increasing, the localization in position is more accurate, so, for the Uncertainty principle, electrons are forced to occupy higher and higher momentum states, and the maximum value of the momentum (called Fermi-momentum) shifts. At $T = 0$ there is the condition of complete electron degeneracy (it is a good approximation also for low T). In the equation of state for degenerate matter, the pressure is independent of T

$$P \propto \rho^{const} \tag{1.3}$$

Where ρ is the density and the constant exponent is $\frac{5}{3}$ in non-relativistic regime and $\frac{4}{3}$ in extremely-relativistic regime. The transition between these two different regimes depends on the density and usually takes place at a typical $\rho_{tr} \sim 10^6 \mu_e g cm^{-3}$ (where μ_e is the mean molecular weight for electrons). Different regime for the equation of state as a function of T and ρ are shown in fig. [1.4].

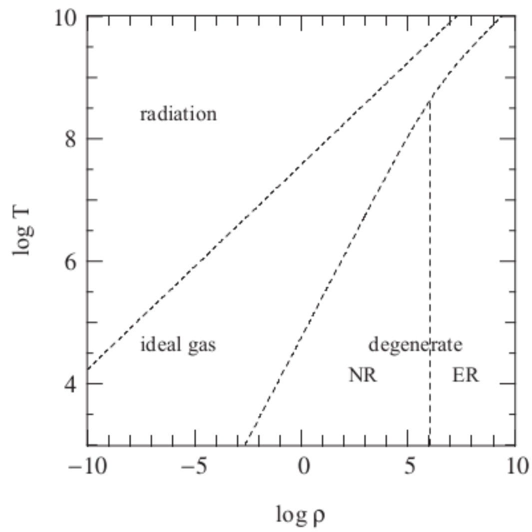


Figure 1.4: Different regimes for the equation of state for a gas of free particles in the $(\log\rho, \log T)$ plane; the dashed lines are approximate boundaries between regions of different regimes.

White Dwarfs are degenerate stars: they do not have to be hot to be in hydrostatic equilibrium, the electron degeneracy allows them to remain in hydrostatic equilibrium even when they cool down.

1.4.2 WD and Chandrasekhar limit

Without nuclear fuel, the energy of a WD decreases due to radiation; this implies that the star contracts. This process cannot continues until the radius goes to zero. The consequence of contraction is an increase of the density, until the critical value ρ_{tr} is reached and the transition between non-relativistic and extremely-relativistic regime takes places. Chandrasekhar in 1930 [Chandrasekhar, 1931], taking into account special relativistic effects in the degenerate electron equation of state, discovered that it exists a maximum mass for an extremely relativistic fully degenerate structure to be in hydrostatic equilibrium; this was called Chandrasekhar mass (Ch-mass):

$$M_{Ch} = 1.459(\frac{2}{\mu_e})^2 M_\odot \tag{1.4}$$

(where μ_e is the average mass per free electron). To compute this value there are several effects which have to be considered, and which contribute to lower the limit, such as electrostatic interactions and electron capture. The usual value for the Chandrasekhar limit (Ch-limit) is $M_{Ch} \sim 1.39 M_{\odot}$.

1.4.3 SNe Ia and carbon-oxygen WDs

A Type Ia Supernova is believed to origin from the disruption of a carbon-oxygen white dwarf (CO-WD) which reaches the Chandrasekhar limit.
CO-WDs are stars that, after the central H- and He-burning phases, develop a highly electron degenerate CO core. After the thermally pulsing asymptotic giant branch phase, these stars eject the whole envelope leaving the CO core. A WD is thus formed by a CO core eventually surrounded by thin layers of lighter elements.
According to theoretical models, the initial-final mass relation (IFMR) links the mass of a star on the main sequence (M_i), with the mass of the WD left at the end of its evolution (M_f): grouping stars in different ranges of initial masses depending on their final fate [Herwig, 2005], stars with $M_i \leq M_{up} \approx 6 - 8 M_{\odot}$ [Siess, 2007] are expected to leave CO-WDs as remnants.
In order to be able to reach the Ch-limit (according to the most uniformly well-accepted models), CO-WDs are generally believed to be stars of about one solar mass.
The semi-empirical IFMR indicates that WDs of about $1 M_{\odot}$ originate from intermediate-mass stars with initial masses in the range $M_i \approx 5 - 7 M_{\odot}$.
Moreover, assuming that these WD progenitor stars do not experience the third dredge-up, they would be able to reach the Ch-limit and thus to explode as SN Ia. [Marigo, 2013]

1.5 Importance of SNe Ia

Supernovae are important for several reasons.

1. Nucleosynthesis.
   During the evolution of the star before explosion, light elements are burnt into heavier elements in an exothermic process.
   SNe Ia contribute very significantly, with an explosive nucleosynthesis, to the Fe-peak elements, while the production of lighter elements is less important. The first calculations of the SN Ia nucleosynthesis were made by Iwamoto, Brachwitz Nomoto et al. [Iwamoto et al., 1999]). More recent calculations have been made by Woosley, Kerstein, Sankaran & Ropke [Woosley et al., 2009]). The final composition of the SN Ia is ^{56}Ni in the central parts, while lighter elements (such as Ca, S, Si) are present in more external layers. The mass fraction of the major nuclei producted in the nucleosynthesis in the W7 model (C-deflagration) is shown in fig. [1.5].

2. SNe Ia as standard candles.
   Cosmic acceleration and dark energy.
   The SNe Ia present a quite homogeneity in their lightcurves (since they are believed to originate from the explosion of a WD with the uniform mass of $M_{Ch} \sim 1.39 M_{\odot}$). They reach a peak in absolute magnitude of $M_V \approx M_B \approx -19.30 \pm 0.03 + 5\log(\frac{H_0}{60})$. Since they have long-lived progenitors (so they are found in all type of galaxies, also the ellipticals) and since they can be easily identificated, they represent a useful

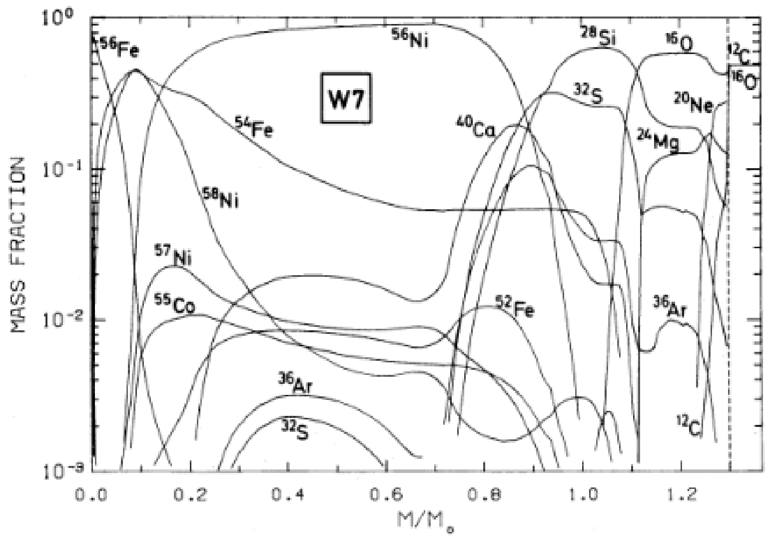


Figure 1.5: Mass fraction of a few major nuclei resulting from C-deflagration predicted by W7-model [Nomoto et al., 1984]

tool to estimate the distances. Once the apparent magnitude (m) in measured, the distance can be obtained

$$m - M = -5 + \log_{10} d \tag{1.5}$$

(where d is the distance expressed in parsec). The use of type Ia supernovae as distance indicators, led S. Perlmutter, B. Schmidt [Perlmutter and Schmidt, 2003] and A. Riess [Riess et al., 1998] to the Nobel in 2011. From the observation and tabulation of numerous SNe Ia, they note that the average observed magnitude were higher than expected, therefore the fluxes were fainter and hence the distance greater.

The explanation has been found in the fact that the universe does not expands in a constant or decelerate manner (as expected by the presence of gravitating matter) but in an accelerated way. This is thought to be due to the presence of a further component, the dark energy, which seems to be predominant and to cause the accelerated expansion rate. From the SNe Ia distribution, the final prospect of the different components in the universe is: $\Omega_m = 0.27$ (the gravitating matter, i.e. dark matter and baryonic matter) and $\Omega_\Lambda = 0.73$ (the dark energy).

Recently, however, P. Milne et al. [Brown et al., 2014] seem to have distinguished two different classes of SNe Ia from the observation in the UV band. These differences between the class of the "standard candle" could lead to constrain and probably to reduce the accelerate rate of cosmic expansion. However the statistics have to be improved and this result confirmed.

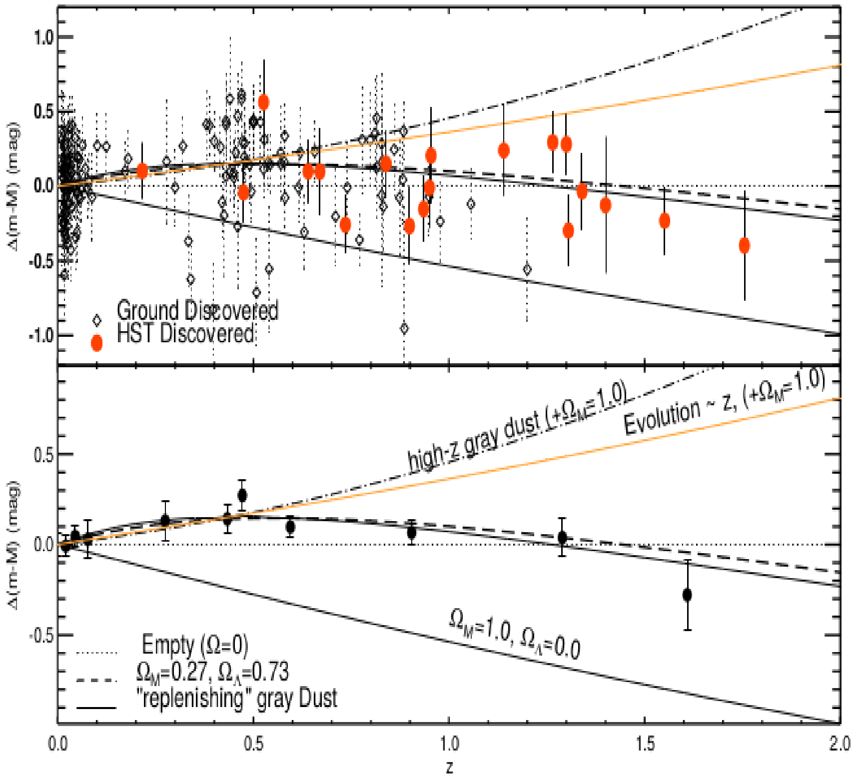


Figure 1.6: In the figure the observed magnitude normalized to the value for Milne's model ($\Omega_m = 0$) is tabulated against the redshift. Between $z \approx 0.2$ and $z \approx 1$, the observed data exceed the Milne's model. [Riess et al., 2004]

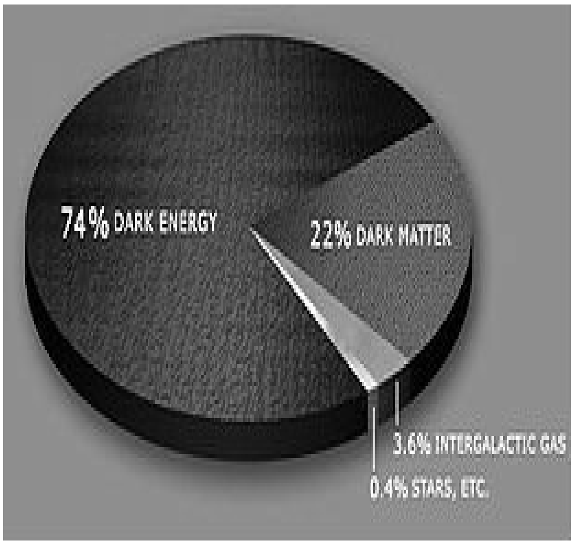


Figure 1.7: Percentual values of the different components in the Universe.

Chapter 2

Binary systems as SNe Ia progenitors.

Single-Degenerate and Double-Degenerate configurations.

Chandrasekhar and sub-Chandrasekhar models.

Core-degenerate configuration.

Type Ia Supernovae are believed to origin from the thermonuclear explosion of a carbon-oxygen white dwarf which reaches the Chandrasekhar limit. Therefore the WD, which has an initial mass of about $1M_{\odot}$, has to gain mass to reach the critical value of $1.39M_{\odot}$, and, taking into account the efficiency of this process, the only way to reach this limit seems to be the accretion of the mass from a companion star in a binary system. At this point two different evolutionary channels can be distinguished: single-degenerate scenario (SD), in which a CO-WD gradually accretes material from a non-degenerate companion star, and double-degenerate scenario (DD), in which the donor star is itself a WD and the explosion results in a merger-like event. These models, in which the WD has to reach the Ch-mass to originate a SN Ia explosion, are called Chandrasekhar-models. Beyond them there is an alternative class of models in which a SN Ia explosion could occur even if the WD does not reach Ch-limit: these are the sub-Chandrasekhar models. Actually the Ch-models are the most accredited since they could explain the homogeneous nature of the SNe Ia.

2.1 The origin of Single-Degenerate and Double-Degenerate configuration

The standard evolutionary scenario to SN Ia explosion starts with a close binary system in which the primary is an intermediate mass star, so that the first Roche lobe overflow (RLOF) leaves a CO-WD. Even low mass stars ($M \leq 2M_{\odot}$) can produce CO-WDs, but in close binary this can happen only if the first mass exchange takes places after the He-flash. However, low mass stars are thought to produce a He-WD rather than a CO-WD. Therefore, reasonable limits to the primary mass (m_1) in SN Ia progenitor systems are $2M_{\odot} \leq M \leq 8M_{\odot}$. When the secondary fill its Roche lobe (RL) there are two possibilities:

- The CO-WD accretes and burns the H-rich material remaining compact inside its RL;

- A common envelope (CE) forms around the two stars.

In the first case the WD grows in mass and a certain point a SN Ia explosion occurs; in the second case the CE is eventually expelled (due to the action of a frictional drag force), while the binary system shrinks [Iben Jr and Tutukov, 1987]. If the secondary is relatively massive, the outcome is a CO-WD + He star system. The He star expands and fills its RL, pouring He-rich material on the companion which has again the possibility of accreting material and growing up to explosion conditions ([Iben Jr and Tutukov, 1994], [Wang et al., 2009]).
Both these paths are SD channels, with the important difference that in the first one some H is expected to be present in the spectrum (H-rich SD channel), while in the second one no H-rich material is expected to be present (Helium star channel). If the CO-WD does not accrete He from the companion, a CE phase sets in again, leading to a close CO + CO-WD system. The loss of angular momentum via gravitational wave radiation can lead the system to merge, and, if the combined mass exceeds the Ch-limit, an explosion can occurs. This is the DD channel to SN Ia. A DD system can be formed also when the secondary is a low mass star, which fills its RL when its He core is degenerate; in this case the CE phase leaves a CO + He-WD system. Since the combined mass is typically smaller than Chandrasekhar one, this channel provides mainly sub-Ch events. [Greggio, 2010]

2.2 Single-Degenerate Scenario in Chandrasekhar models

Whelan & Iben (1973) [Whelan and Iben Jr, 1973] were the first to propose a binary configuration of a carbon-oxygen white dwarf (CO-WD) and a non-degenerate companion (they proposed a red giant) as a progenitor system of Type I supernovae. They derived the physical features of the pre-supernova system and then provided a statistic of SN Ia events considering the "*Sixth Catalogue of the Orbital Elements of Spectroscopic Binary Systems*" [Batten, 1967]: they obtained an average frequency of SNe I equal to 1 per 50 years (consistent with Tammann [Tammann, 1970]). in conclusion, the near uniqueness of the mass of the primary at outburst in this model is in agreement with the homogeneity of the light-curve; Whelan & Iben also suggest that a spherical symmetric explosion may possibly contribute to the homogeneity of SNe I light curves. An argument against this formulation is the dependence on the rate of mass transfer from the secondary to the primary: it cannot be too fast or to slow, in order to produce a shock wave that, in this model, on passing into the dense interior, might heat up matter sufficiently to cause the detonation of carbon.

2.2.1 Progenitor candidates

Since the WD is accreting material from a secondary non-degenerate companion star, virtually every type of close binary has been suggested as a SN Ia progenitor, but one of the defining characteristics of this type of SNe is the absence of H or He in the spectrum at any time during the outburst or decline. This absence rules out most of the proposed close binary progenitors ([Starrfield et al., 2011], [Howell, 2011]). There are several possibilities for the WD companion in SD scenario: mainly the donor star is thought to be a main sequence (MS) star, a red giant (RG) or subgiant star, an asymptotic giant branch (AGB) star; a more particular configuration considers a WD in a binary system with a Helium (He) star (which can be again a MS or a subgiant star).

Recurrent novae

A favourite class of candidates for SNe Ia explosion seems to be the recurrent novae (RNe), a small heterogeneous group of cataclysmic variables that exhibit nova outbursts at intervals of the order of decades [Anupama, 2011]. There are ten known galactic RNe, and a few more suspected ones, while two are known in the Large Magellanic Cloud, and a few suspected systems in M31. The components are a hot, massive white dwarf ($M_{WD} \geq 1.2M_{\odot}$) which accretes mass from an evolved companion with mass transfer rates $10^{-8} - 10^{-7}M_{\odot}yr^{-1}$. This group of cataclysmic variables can be divided in Long Period Binaries (which have orbital periods of several hundred days) and Short Period Binaries (which have orbital period of a day or a few hours). This latter section can be further sub-grouped: the U-Sco class (fast novae) and the T-Pyx class (slow novae), with the propertied reported in the following table:

Name	m_{max}	m_{min}	t_3 [d]	$< t_{rec}$ [yr]	distance [kpc]	secondary	P_{orb} [d]	Outburst [year]
Long Period Binaries - T Crb/RS Oph Class								
T CrB	2.5	9.8	6	80	0.9	M3 III	227.67	1866,1946
RS Oph	4.8	11.0	14	22	1.6	M0/2 III	455.72	1898, 1907, 1933 1945, 1958, 1967, 1985, 2006
V3890 Sgr	8.1	15.5	17.0	27	7.0	M5 III	519.7	1962, 1990
V745 Sco	9.4	18.6	14.9	52	7.8	M6 III	510	1937, 1989
Short Period Binaries - U Sco Class								
U Sco	7.5	17.6	4.3	22	12.0	K2 IV	1.23	1863, 1906, 1917 1936, 1979, 1987, 1999, 2010
V394 CrA	7.2	18.4	5.5	38	10.0	K	1.52	1949, 1987
V2487 Oph	9.5	17.3	8	40?	12.0		~ 1	1900, 1998
Short Period Binaries - T Pyx Class								
T Pyx	6.4	15.5	62	19	5.0		0.076	1890, 1902, 1920, 1944, 1966, 2011
CI Aql	9.0	16.7	32	42	5.0	K-M IV:	0.6184	1917, 1941, 2000
IM Nor	8.5	18.3	80	82	3.4		0.1026	1920, 2002

Figure 2.1: Basic parameters of galactic recurrent novae [Anupama, 2011].

The estimates of mass ejected during the outburst in the fast RNe systems (Short Period Binaries), and theoretical models indicate that not all the accreted material is ejected during an outburst (e.g. [Kahabka et al., 1999], [Anupama and Dewangan, 2000], [Hachisu et al., 2007]). This implies that the WD in these systems could increase its mass, and in the event of it being a CO-WD the increase in mass could lead to a supernova explosion. Observing emission lines and X-ray evolution of two non-symbiotic type RNe, Nova LMC 2009a (slow nova) and U Sco (fast nova), it has been proposed that are similar systems in different stages of secular evolution (the slower Nova LMC 2009a is in a much earlier secular phase). Both RNe are expected to be on the evolutionary tracks toward SN Ia explosion [Orio et al., 2011]. Also other RNe such as Cl Aquilae (slow nova), RS Ophiuchi and T Coronae Borealis (Long Period Binaries) consist of a system in which the WD is close to Ch-limit ([Sahman and Dhillon, 2011], [Mohamed et al., 2011], [Tatarnikova et al., 2011]) and, considering the mass accretion rates, they are SN Ia candidates. Although just a few RNe are currently known, the true number of RNe is likely to be much larger. A new proposal for the detection of undiscovered RNe come from the observed fact that some of them are luminous, hard X-ray sources; even if the fraction of such systems among RNe is unknown, this offers an alternative new method to UV and optical spectroscopy for discovering RNe candidates [Mukai et al., 2011].

Symbiotic stars

Symbiotic stars are long-period binaries in which an evolved RG transfers material to a hot and luminous companion surrounded by an ionized nebula. The hot component is predominantly a WD orbiting close enough to the RG that it can accrete material from its wind rather than through the Roche lobe overflow (RLOF). They can be divided in S-type (with normal RG and orbital period of about 1-15 years) and the D-type (with Mira primaries usually surrounded by a warm dust shell, and orbital period usually longer than 10 years). However there is an increasing number of systems in which RLOF seems to be quite common: in S-type symbiotic stars and in the symbiotic recurrent novae (SyRNe). Such novae are rare: only four SyRNe are known. The RLOF associated with tidally distorted donors is important in relation to symbiotic stars as possible SN Ia progenitors: the high mass transfer rate would allow the WD to gain significant portion of the RG envelope and it would lead the WD to the Ch-limit. ([Mikołajewska, 2011], [Mikolajewska, 2008]).

Helium star donor channel

A CO-WD can also accrete material from a He star to increase its mass to the Ch-limit and it can produce a SN Ia explosion via C-deflagration. This is known as "*Helium star donor channel*". Massive WD + He-star systems are candidates of SN Ia progenitors. HD 49798RX J0648.0-4418 provides existence of these systems. This is a candidate SN Ia progenitor [Wang and Han, 2011]. Another similar system is the helium nova V445 Pup, in which WD mass is estimated to be very high ($M \geq 1.35 M_{\odot}$) and it is accreting in mass. [Kato, 2011a].

2.2.2 Hunting SNe Ia progenitors

An ideal way to identify the progenitors of supernovae, is to search for changes between images taken before and after the explosion. While successful for core-collapse supernovae, whose progenitors are the brightest of the stars, this approach is more challenging for SN Ia, since the pre-explosion luminosities of even the brightest progenitors are generally too low. In absolute terms, prior to the explosion, the progenitor WD is a faint star. Therefore its optical detection is out of discussion, at least for extra-galactic events. However, the companion star might be detectable, depending on its luminosity, similarly to core-collapse events [Smartt, 2009]. This was attempted for a number of SNe Ia ([Maoz and Mannucci, 2008], [Smartt, 2009]), but the limits were not sufficiently stringent to rule out any of the possibilities. Things changed substantially with the very recent discovery of the nearby SN 2011fe in M101 ($d \approx 6Mpc$). Based on pre-explosion HST images, Li et al. [Li et al., 2011a] were able to place a limit that rules out a RG star (and hence a symbiotic system like RS Oph for this particular event) and a He-star as WD companion, favouring instead a MS star or a DD configuration (that are consistent with the data) [Patat et al., 2011]. In the early 1990's, a new way of detection was proposed: the progenitors could be discovered as bright X-ray sources; therefore, they would be detectable even in external galaxies.

SN Ia and Supersoft X-ray sources

The new perspective of detecting SN Ia progenitors as bright X-ray sources came from the discovery of supersoft X-ray sources (SSSs), with luminosities greater than $10^{36} ergs^{-1}$ and values of kT in the range of tens of eV. These emissions are expected in the epoch during which mass is incident on a WD at a high rates ($10^{-7} M_{\odot} yr^{-1}$). These epochs are expected both in the SD and DD progenitors, and also in binaries in which the WD will not achieve the Ch-limit. High rate accretion produces high luminosities; in addition, most calculations show that quasisteady or episodic nuclear burning can occur, increasing the luminosity by more than a order of magnitude. If the photosphere is not much larger than the WD, the emission will have values of kT in the range of tens of eV and the source will appear as a luminous supersoft X-ray source. A link to SNe Ia was established by the first population synthesis of nuclear-burning WDs (NBWDs), which showed that enough CO-WDs could be brought to the Ch-mass to make possible that NBWDs in close binaries could be the dominant contributors to the rate of SNe Ia ([Rappaport et al., 1994], [Di Stefano et al., 1997]). The link probed by these calculations is however the physical connection between NBWDs and SNe Ia, not the connection between NBWDs and SSSs. Further studies will be necessary to derive the appearance of NBWDs [Di Stefano, 2011].

If steady burning WDs do indeed look like SSSs and the SD scenario is the dominant contributor to SNe Ia rate, it should be expected to see a corresponding population of SSSs large enough to produce the SNe Ia rate. However the number of observed SSSs in both the Milky Way and external galaxies appears to be at least 1-2 orders of magnitude too low to account for the number of observed SNe Ia, both in spiral and elliptical galaxies ([Gilfanov and Bogdán, 2010], [Di Stefano, 2010]). There are therefore two alternatives:

- SSSs are not the dominant contributors to the SNe Ia rate;
- the energy emerges in other wavelengths: for example, if the photosphere of NBWD is large enough the bulk of radiation emerges in the ultraviolet (UV); if heavy winds are present the radiation emitted by the WD is absorbed and re-emitted in the infrared (IR) [Di Stefano, 2011].

The latter perspective implies that SSSs exist but are somehow hidden from view of our current observational capabilities during their supersoft phase, only to become visible when they explode as SNe Ia. This has been modeled for Large Magellanic Cloud (LMC) sources [Nielsen et al., 2011]: it appears possible to obscure a canonical SSS (orbital separation $1AU$, $kT_{peak} \sim 50eV$) within the wind of a companion star, so that it's no longer observable as an SSS to Chandra's ACIS-I detector. The wind mass loss rates have to be comparable to the amount of matter accreted unto the WD component in the steady-burning phase ($10^{-7} M_{\odot} yr^{-1}$).

Three phases towards SN Ia

M. Kato, however, criticizes this way to proceed. It is suggested that in the SD scenario, in each of the two main channels, WD + MS and WD + RG, a typical binary undergoes three evolutionary stages before explosion: the wind phase, SSS phase and RNe phase, in this order because the accretion rate decreases with time as the companion mass decreases [Kato, 2011b].

Evidence of the SSS phase would be CAL 83 and CAL 87 in the LMC (WD + MS) [Van den Heuvel et al., 1992] and the symbiotic stars SMC3 and Lin358 (WD + RG) in the Small Magellanic Cloud (SMC).

In order to constrain progenitor models in early-type galaxies, Gilfanov & Bogdán [Gilfanov and Bogdán, 2010] obtained supersoft X-ray luminosity for several early-type

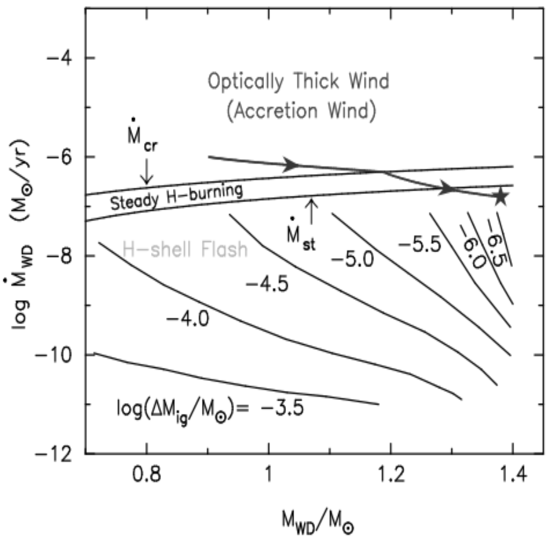


Figure 2.2: Typical evolutionary path of a SN Ia progenitor in the SD scenario: starting from the accretion wind phase, the binary enters the SSS phase (narrow region between M_{cr} and M_{st}); when the mass accretion rate decreases to less than the value to keep steady H-burning (M_{st}), the binary enters the RNe phase (very weak shell flash). The WD explodes at the starmark as an SN Ia. [Hachisu et al., 2010]

galaxies. They concluded that these fluxes are much smaller than those expected from the SD scenario, and thus it is not the major path to SNe Ia. On the other hand, Hachisu et al. (2010) [Hachisu et al., 2010], considering the same data, concluded that the observed X-ray luminosities are very consistent with the SD scenario and thus, it is a strong observational support for the SD. Gilfanov & Bogdán [Gilfanov and Bogdán, 2010], in M. Kato perspective, were wrong to assume that all the WDs always stay in the SSS phase before the SN Ia explosion (i.e. $2x10^6 yr$ for a $1.2 M_\odot$ WD to reach the Ch-limit with an accretion rate of $10^{-7} M_\odot yr^{-1}$). This assumption for a WD is however very unlikely: this would mean that the WD always evolves along the narrow strip of 'steady H-burning', while it is a relatively short fraction of the total lifetime.
Hachisu et al. [Hachisu et al., 2010] followed the evolution of a number of binaries with different binaries parameters (fig. [2.2]) and found that the SSS phase is as short as $P = 2.5^{+0.9}_{-1.8} x 10^5 yr$.
The comparison of the results obtained by Gilfanov & Bogdán (GB10) and by Hachisu et al. (HKN10) is reported in the table [2.3].

There is another class of NBWDs: the ones which are accreting above the steady nuclear burning rate, but below the Eddington limit ($\dot{M}_{Edd} = 10^{-5} M_\odot yr^{-1}$). These WDs will have a H-burning layer over the degenerate core, with an extended envelope. They do not emit as SSSs since the envelope is thick enough to absorb soft X-rays; the peak emission is shifted to longer wavelengths, the far UV. These objects are called ultra-soft sources (USSs) and they have been proposed as possible SN Ia progenitors [Lepo and van Kerkwijk, 2011].

Galaxy	$N_{\mathrm{WD,SSS}}$ GB10[b]	$N_{\mathrm{WD,SSS}}$ HKN10[b]	l_{X}^{a} 10^{35} erg s^{-1} GB10	l_{X}^{a} 10^{35} erg s^{-1} HKN10	$L_{\mathrm{X,SSS}}$ 10^{37} erg s^{-1} GB10	$L_{\mathrm{X,obs}}$ 10^{37} erg s^{-1} GB10	$L_{\mathrm{X,SSS}}$ 10^{37} erg s^{-1} HKN10
M32	25	3.7	28	3.1	7.1	0.15	0.12
NGC3377	580	88	47	5.8	270	4.7	5.1
M31 Bulge	1100	160	21	2.9	230	6.3	4.7
M105	1200	180	46	5.9	550	8.3	11
NGC4278	1600	240	48	7.2	760	15	17
NGC3585	4400	660	31	3.5	1400	38	23

Figure 2.3: SSS in early-type galaxies (0.3-0.7 keV) [Kato, 2011b].

2.2.3 SN Ia remnants. Detection of the WD companion

SN Ia remnants and Circumstellar medium

Some important informations on the progenitors can be gained analysing young SN remnants: their properties are linked to the structure of the medium in which they expand. The impact of the SN ejecta on any companion star would shock the ejecta, leaving observational signatures in the spectra [Howell, 2011]. It is possible not to see the signs of this direct interaction because there is no (or not enough) circumstellar material (CSM). An alternative approach to the problem was proposed and applied recently [Patat et al., 2007]: since the SNe Ia are weak UV sources, they are not able to ionize CSM at large distance. Therefore, provided that the gas is placed along the line of sight, it can be revealed by strong optical absorption lines like Ca II, H& K, Na I D and K I. These lines can be distinguished by the ones generated within an interstellar medium (ISM) cloud placed along the line of sight because the formers show a time variation: the CSM close to the explosion site is initially ionized and then, as the SN fades away, it recombines and the lines get more intense. Once the CSM is reached by the SN ejecta, the interaction would re-ionize the material, causing the absorption features to disappear. Analyzing the change of the lines, given the SN ejecta velocity, one can deduce the distance of the material from the SN. This technique was first applied to SN 2006X, for which a series of high resolution spectra with the VLT+UVES is obtained. The two epoch observations show an evident change in the line profile of Na I D ([Patat et al., 2007], [Patat et al., 2011]). The conclusion is that these features originate either in the wind of a red giant or in the remnant shells of sucessive nova outbursts. Both possibilities favored the SD scenario. The recent study of Sternberg et al. [Sternberg et al., 2011] has shown a significant excess of blue-shifted Na I features in SNe Ia, which are interpreted as a systematic sign of gas outflows at velocities ranging from a few $10km/s$ to more than $100km/s$. These would indicate that the SD channel (with possible sub-channels) dominates over the DD channel.

Detection of the companion star

If the pre-explosion system is formed by a WD accreting material from a non-degenerate companion star, the latter is supposed to survive the explosion. As a consequence of the WD disruption, it gets a gravitational kick, and it runs away at an unusually high speed, if compared to all other field stars. On the contrary, assuming the SN Ia explosion as the result of the merger of two WDs in DD scenario, no surviving companion is predicted.
Therefore if the WD remnant companion was found for a particular event, this would

clearly testify in favour of a SD system for that specific event.
Since this detection requires multi-epoch accurate astrometry of the field surrounding the SN Ia site, the method can be applied only to historical SNe Ia in the Galaxy. [Patat et al., 2011]

The features of post-explosion donor star W.E. Kerzendorf [Kerzendorf, 2011] provides three possible features of a donor star after the explosion: unusual kinematics, unusual rotation and unusual state (luminosity).
After the explosion, the donor star get flung from the site with the previous orbital velocity [Han, 2008]; in addition the SNa ejecta impart a kick to the donor star, which is normally much smaller then the orbital velocities [Canal et al., 2001].
During the RLOF phase, the donor star will tidally couple and will inherit post-explosion the orbital frequency of the system as stellar rotation [Han, 2008] (with the caveat that the stellar rotation is measured via its line broadening effects and thus is attenuated by a factor $\sin i$, being i the inclination angle).
The state of the donor star after the explosion, in particular the luminosity and the state of the envelope, depends on the nature of the donor star; in addition the simulations [Marietta et al., 2000] show that all of the companions are unlikely to accrete much of the ejecta and thus probably will not show any abundance anomalies. In summary, the surviving donor star is expected to be luminous, with a slightly unusual velocity and probably high rotation. The results of calculations of the properties for different classes of donor star are reported in the table:

	Velocity	**Rotation**	**State**
MS donor	$200\text{Km} \cdot s^{-1}$	$150\text{Km} \cdot s^{-1}$	Over-luminous. Keep most of the envelope
Subgiant donor	$150\text{Km} \cdot s^{-1}$	$100\text{Km} \cdot s^{-1}$	Over-luminous. Keep most of the envelope
Giant donor	$80\text{Km} \cdot s^{-1}$	$60\text{Km} \cdot s^{-1}$	Under-luminous. Lose most of the envelope

Hystorical SNe Ia: search for the donor remnants There are three historical SNe Ia in our galaxy: SN 1006, SN 1572 (Tycho), SN 1604 (Kepler) and several observations have been made in order to detect and to put constraints on the nature of the progenitors.

- *SN 1006*
  The supernova remnants (SNR) of SN 1006 have been recently studied by P. Ruiz-Lapuente et al. [Ruiz-Lapuente et al., 2011] and by W.E. Kerzendorf [Kerzendorf, 2011]. P. Ruiz-Lapuente et al. used UVES at the VLT to get the stellar parameters and the abundance patterns of star inside the 20% of radius of the SNR. W.E. Kerzendorf used the multi-object high-resolution spectrograph FLAMES to analyze the possible candidates within a radius of 120".
  Both the analyses show no unusual star within the fixed radius. A RG and a subgiant donor are excluded; the system could be consistent with the DD scenario.
- *SN 1572 (Tycho's SNa)*
  The Tycho's SNa was studied by P. Ruiz-Lapuente et al. [Ruiz-Lapuente et al., 2004]. The survey excluded an over-luminous object and a blue star, as there were none in the field; RG and He-star were also discarded as possible companions. A star with metallicity close to solar and moving at high speed for its distance was suggested as

the likely surviving companion of the exploding WD that produced the SNa. This star denoted with Tycho-G has coordinates $\alpha = 00^h25^m23.7^s$ and $\delta = +64°08'02''$. For its unusual radial velocity and proper motion the object has been considered a good donor remnant candidate. Several caveats however have been found: the main is the seemingly large distance to the remnant's geometric center in the plane of the sky; moreover, although the radial velocity and the stellar parameters have been confirmed [Kerzendorf et al., 2009] by using Subaru HDS spectroscopy, no rotation for Tycho-G has been found. Kerzendorf [Kerzendorf, 2011] analyzes the parameters of Tycho-G and in particular its anomalous proper motion, finding it comparable with the one of similar stars from the proper motion catalogue PPMXL [Roeeser et al., 2010]. This suggests that Tycho-G is an unrelated background star. Furthermore from the observations another promising candidate has emerged [Kerzendorf, 2011], Tycho-B, with a very high rotation. Further analyses have however shown that it has no high velocity, so it is believed to be a foreground object. In summary, none of these candidate are likely donors. Also for this event the DD scenario could be plausible.

- *SN 1604 (Kepler's SNa)*
  Considering another type of analyses, based on the kinematics and morphology of the Kepler's SNR and the chemical composition of its northern shell, A. Chiotellis et al. [Chiotellis et al., 2011] argue that Kepler's SN had a symbiotic binary progenitor consisting of a CO-WD and a $4 - 5M_\odot$ AGB donor star.

- *SNR 0509-67.5*
  This supernova, which occurred approximately 400 years ago in the LMC, was confirmed to be a SN Ia by Rest et al. [Rest et al., 2005]. A. Pagnotta and B. E. Schaefer [Schaefer and Pagnotta, 2012] analyze the presence of a leftover companion within the error circle of radius of 1.60". No possible candidates have been found with the required properties: No RGs, no subgiants, no MS stars greater than $1.16M_\odot$. All the SD models are eliminated, so, this particular SN Ia is supposed to have DD progenitor system.

2.3 Double-Degenerate scenario in Chandrasekhar models

In this scenario, SN Ia event arises from a binary system made of two CO-WDs with total mass larger than Ch-limit and with an initial orbital separation small enough to allow the merging of the two components via gravitational wave radiation (GWR) on a timescale smaller than the Hubble time [Iben Jr and Tutukov, 1984], [Webbink, 1984]. The less massive star overfills its own RL and completely tidally disrupts [Benz et al., 1990]. The debris of this WD forms a hot and thick accretion disk around the more massive surviving WD and the matter is transferred to this component [Tutukov and Yungelson, 1979].

2.3.1 Double-Degenerate scenario and accretion induced collapse

The main shortcoming of this model is a theoretical one.
In the merger process, carbon is expected to ignite off-center, near the surface [Mochkovitch and Livio, 1990]: the carbon flame moves inward by heat conduction to reach the center [Saio and Nomoto, 1985], [Saio and Nomoto, 1998] and the released nuclear energy is lost in neutrinos, converting the CO-WD into a oxygen-neon-magnesium core (ONeMg core) [Kawai et al., 1987]. Electron capture on Ne and Mg is expected to

lead to an accretion induced collapse (AIC) of the ONeMg core into a neutron star, rather than into a SN Ia explosion. This has been excluded by Lorén-Aguilar, Isern & Garcia-Berro [Lorén-Aguilar et al., 2009], who find that early C-burning indeed occurs, but it is soon extinguished.
A second problem rises after the merging: the mass transfer from the disc to the surviving WD occurs at very high rate, close to the Eddington limit ($\dot{M}_{Edd} \approx 10^{-5} M_\odot \cdot \mathrm{yr}^{-1}$), so the off-center C-burning has to occur at the base of the accreted layers before the WD reaches the Ch-mass [Saio and Nomoto, 1985], [Saio and Nomoto, 1998]. However, [Piersanti et al., 2003] have shown that, taking into account the effects of the rotation, the process become "self-regulated", eventually producing a degenerate central C-ignition and a SN Ia-like event.

2.3.2 Evolution of the system towards the explosion

A. Tornambé & L. Piersanti [Tornambé and Piersanti, 2013] present an evolutionary model computed with an updated version of the 1D hydrostatic lagrangian evolutionary code FRANEC, first described in Chieffi & Straniero [Chieffi and Straniero, 1989]; they focus only on the behaviour of the accreting WD during the evolution to the explosion, not accounting for the contribution of the accretion disc to the observational features. The evolution in the HR diagram along the accretion phase of a CO-WD with initial mass $M_{WD} = 0.8M_\odot$ is reported in fig. [2.4]. The CO-rich material flows from the disc formed by the disruption of a $0.7M_\odot$ companion during the merging phase.

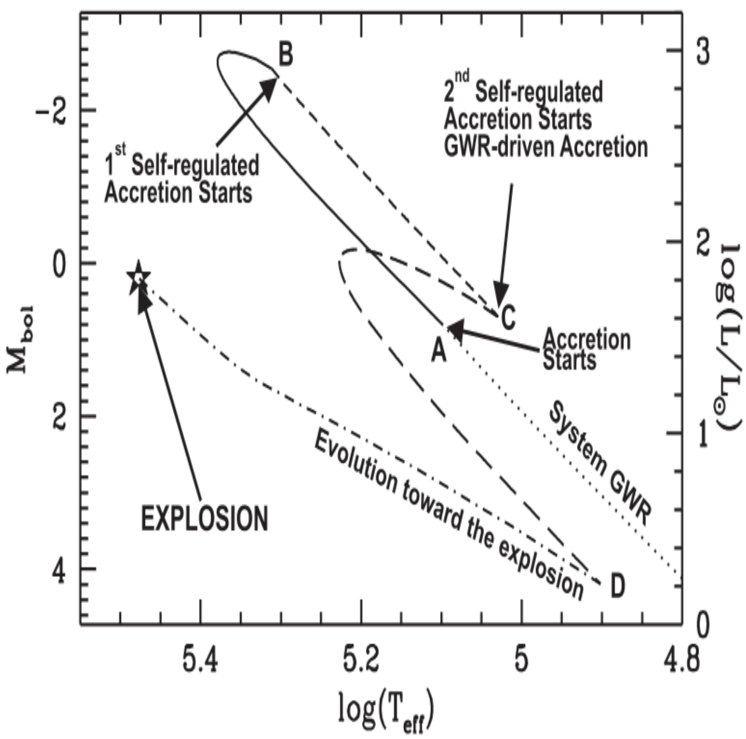


Figure 2.4: Evolution in the HR diagram of a CO-WD with initial mass $M = 0.8M_\odot$ accreting CO-rich matter from a thick disc formed by the $M = 0.7M_\odot$ CO-WD companion during the merging [Tornambé and Piersanti, 2013].

They [Tornambé and Piersanti, 2013] distinguish four different phases in the evolution of the merged object:

- *Constant $\dot{M}$ phase*: initially the matter flows from the WD at a very high rate ($\dot{M} \geq 10^{-5} M_\odot \cdot \mathrm{yr}^{-1}$)d; the external layers heat up, the radius greatly increases. Hence, both the surface luminosity and the temperature increase (solid line in fig. [2.4]);

- *First self-regulated accretion phase*: the accreting WD spins up (due to the deposition of angular momentum by the accreted matter) and the critical rotational velocity is attained for the first time (point B in fig. [2.4]): mass transfer comes to a halt. As a consequence, the WD contracts and recedes from the critical condition, the accretion starts again and proceeds until the critical rotational velocity is attained once more. The rate at which matter is deposited onto the WD reduces with time, so the surface luminosity decreases;

- *GWR-driven accretion-phase*: the continuous deposition of angular momentum increases the rotational energy until this one exceeds a critical fraction of the gravitational energy (point C in fig. [2.4]); Gravitational wave emission sets in and allows the WD to recede from critical condition: the radius decreases, hence surface layers heat up via compression. The surface luminosity increases again (long-dashed line in fig.) until a large part of thermal energy is removed via inward thermal diffusion. When the accreting WD approaches the Ch-mass, the GWR emission ceases (point D in fig. [2.4]);

- *evolution towards the explosion*: this phase is triggered by the loss of angular momentum by the accreted WD. The star contracts homologously and heats up. As a consequence, the surface luminosity increases (dot dashed line in fig. [2.4]) and the WD spins up until the explosion.

Once the SN Ia event takes place, the explosion energy overcomes the binding energy of the star causing its total disruption. In contrast to SD configuration, in the DD model no remnants are expected to survive the explosion.

2.3.3 DD progenitor candidates

There is evidence that several binary systems made of two WDs do exist: it has been observationally demonstrated and most population synthesis calculations agree that mergers of two CO-WDs should be very common. The question is whether or not these systems can originate a SN Ia explosion (for example, the outcome of such mergers depends on the parameters of the merging system).
The normal SNe Ia in DD scenario are believed to originate mainly from a CO+CO-WD system; other configurations contemplate also a CO+He-WD system (which are thought to provide mainly sub-Ch events).

Symbiotic stars

These long-period binaries, previously called into question as possible progenitor candidates in SD scenario, are good candidates also in the DD one.
In fact symbiotic stars are made of a WD and a RG companion which has a degenerate core: if they pass through a common-envelope (CE) phase, they may become close pairs of WDs.
For example, a promising system is AR Pav, with Roche lobe filling giants transferring material to relatively massive WD companion. [Mikołajewska, 2011]

Subdwarves

The best known candidate for a DD progenitor of SN Ia is a binary consisting of a subdwarf (sDW) and a massive WD.
sDWs are old stars which have already passed through the RG stage and have lost most of their mass during their evolution. These objects have very thin hydrogen envelopes around a helium core of about half a solar mass.
Numerous sDW binaries have been analyzed. The companions of most sDWs are late MS stars or WDs. The best known DD SN Ia candidate system is KPD 1930+2752, which has an sWD primary and a massive WD; the combined mass of the system reaches the Ch-limit and the stars will probably merge in 200 Myr. [Geier et al., 2010].

Planetary nebula central stars

Recent works have shown that a few planetary nebula central stars (CSPN) are likely DD binaries (or pre-DD binaries). The bright Eskimo nebula (NGC 2392) and NGC 6026 have been analyzed using 1D (CLOUDY; [Ferland et al., 1998]) and 3D (MOCASSIN; [Ercolano et al., 2003]) photoionization codes to infer the nature of the central binary stars. If these systems are short-period binaries, they are potential SN Ia progenitors. [Danehkar et al., 2011]

2.3.4 DD and SSSs

Under certain circumstances, also DD systems may undergo a SSS phase, but with X-ray emissions one order of magnitude lower than the SD ones ([Yoon et al., 2007], [Di Stefano, 2010]).
Therefore, the detection of SSSs coincident with a SN Ia site would allow a direct analysis of some of the properties of the progenitor system.
This method was applied to SN 2007on (and the progenitor problem was questioned by Roelofs & al. [Roelofs et al., 2008]) and to the recent SN 2011fe, but the data were not sufficient to lean towards one of the two scenarios [Li et al., 2011a].
The limit of this method is that it requires pre-explosion archival X-ray images of the SN Ia site. ([Patat et al., 2011])

2.3.5 Search for DD systems

Surveys

Systematic surveys have been dedicated to the discovery of double-degenerate systems; for example radial-velocity (RV) searches (e.g. [Karl et al., 2003]).
An important project was the ESO SN Ia Progenitor Survey (SPY): more than 1000 WDs were checked for RV-variations; SPY detected about 100 new double degenerate systems but among them only one may fulfill the criteria for progenitor candidates [Napiwotzki et al., 2001].
However, the current lack of candidates seems not to be very significant since only one double WD in one thousand needs to possess the characteristics to match the observed SN Ia rate [Nelemans et al., 2001]. ([Geier et al., 2010], [Ferrario, 2011])

Search for gravitational wave emissions

Gravitational wave detectors such as the Laser Interferometer Space Antenna (LISA) are sensitive to gravitational radiation in the millihertz (mHz) range. Galactic population

of double WD (DWD) binaries is supposed to be the dominant source in this frequency range.
A.Stroeer & al. [Stroeer et al., 2011] are interested in finding possible DD progenitors of SNe Ia in the Milky Way: they generate two-year LISA data stream (in order to estimate any selection biases within the binaries) and use DWD population from Ruiter & al. [Ruiter et al., 2010] modelled for the bulge and the disk of the Galaxy using *StarTrack* population synthesis code [Belczynski et al., 2002].
They compute LISA response to the entire population selecting only those objects which have an integrated signal-to-noise ratio $\rho \geq 5$ and defining as SN Ia progenitors as any DWD with a total mass $M \geq 1.44 M_{\odot}$.
The result is about 500 possible candidates among about 31000 resolved systems with the required features.
The spatial distribution of resolved binaries and SN Ia candidates is shown in fig. [2.5].

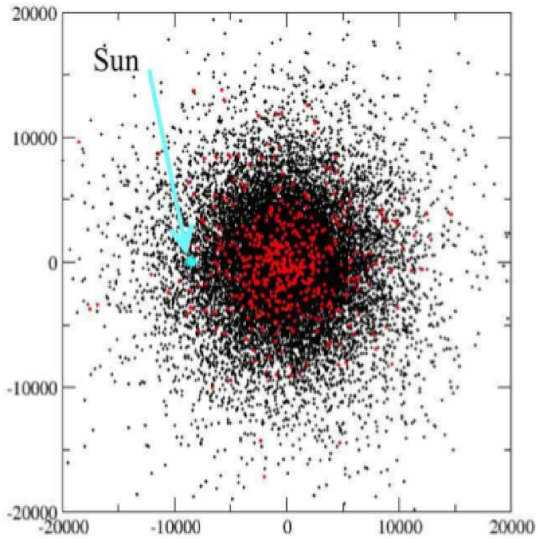


Figure 2.5: Spatial distribution of resolved binaries in the simulation upon the Galaxy in galactocentric coordinates. All binaries are shown in black while potential SNe Ia progenitors are shown in red [Stroeer et al., 2011].

SNe Ia possible progenitors make up about 1.4% of the resolved systems. LISA might be considered an effective tool to identify the Galactic population of DWDs and the SNe Ia candidates within it. [Stroeer et al., 2011]

2.4 Sub-Chandrasekhar models

In sub-Chandrasekhar (sub-Ch) models, SN Ia-like event derives from the thermonuclear disruption of a WD which accretes mass in a binary system but which undergoes the explosion before reaching the Chandrasekhar mass. This class of events is expected to occur both in the SD configuration and in the DD one and it is closely linked to the explosion model.
The strongest argument that motivates investigation of sub-Ch models is the observed rate of SNe Ia: considering this class of models makes it easier to account for the observed rates.

2.4.1 Triggering a detonation of a sub-Chandrasekhar WD

At least two different channels have been proposed as successful progenitor systems in order to produce SN Ia in sub-Ch model:

1. ***Primary CO-WD and He-rich donor star.***

   This is the best studied "*double-detonation*" model, in which a CO-WD accretes He-rich material from a companion star (which can be also a He-WD).

   The outcome of this accretion strongly depends on the mass accretion rate: in order to have He-detonation, a sufficiently massive layer of accreted He needs to be built up and this means that the accretion rate cannot be too high ($\dot{M}_{\rm He} \leq 10^{-8} M_{\odot} \cdot {\rm yr}^{-1}$), as shown in fig. [2.6]

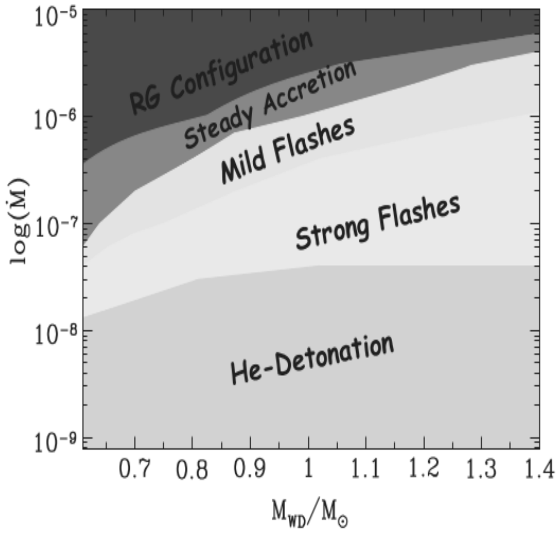


Figure 2.6: Possible accretion regimes in the $(M_{\rm WD}, {\rm log}M)$ plane [Piersanti et al., 2011].

   A surface He-detonation can trigger a secondary detonation of the underlying CO-WD, leading to complete disruption of the star ([Woosley and Weaver, 1994], [Livne and Arnett, 1995], [Sim et al., 2010]).
   Even if the progenitor systems for this mechanism may be rather common, the main drawback for the double-detonation model is that the ejecta are enshrouded by the ashes of the burning of the He layer. The He detonation produces a significant amount of iron-group elements (IGEs) at high velocity: this lead to light curves and spectra that are inconsistent with observation of normal SNe Ia ([Hoeflich et al., 1996], [Nugent, 1997].
   For this reason it is suggested that the He-channel cannot provide progenitors for the majority of normal SNe Ia. ([Piersanti et al., 2011], [Sim et al., 2011])

2. ***Double CO-WD merger***.

   Another SN Ia channel involves the merger of two CO-WDs whose total mass is below Ch-limit.

   Pakmor et al. [Pakmor et al., 2010] have argued that prompt detonation might occur in such a merger if the mass-ratio is high.

   Van Kerkwijk et al. [Van Kerkwijk et al., 2010] discuss another possibility: rather than having detonation triggered during a violent merger, they argue that it might occur later due to compressional heating as the material from the secondary is accreted.

This channel shows several advantages. If most merging CO-WD binaries are assumed to result in SNe Ia, it would account for the observed SNe Ia rate [Van Kerkwijk et al., 2010]. Since lower-mass CO-WDs generally derive from lower-mass stars, it also explains the observed decrease of typical SN Ia luminosity at host stellar population age increasing.

Furthermore, S.A. Sim et al. [Sim et al., 2010] have recently shown that sub-Ch detonations can produce observed features very similar to the ones of SNe Ia: they perform nucleosynthesis and radiative transfer calculations and obtain that for WDs with mass $M_{\mathrm{WD}} \approx 1M_{\odot}$ the amount of IGEs (predominantly ^{56}Ni) and the amount of intermediate-mass elements are comparable to the ones required to account for the brightness and the characteristic spectral features of normal SNe Ia; the synthetic spectra and light curves derived from the simulations agree quite well with the observations.

However, late-phase observations of SNe Ia indicate that a significant mass of stable IGEs (mostly ^{54}Fe and ^{58}Ni) are produced in the explosion ($0.1M_{\odot} \leq M_{IGEs} \leq 0.3M_{\odot}$, Mazzali et al. (2007)). This is an important restriction for sub-Ch models and even if it has been demonstrated that a non negligible mass of stable IGEs can be produced in sub-Ch detonation models, it needs further investigations.

2.5 Super-Chandrasekhar explosions

Recent discoveries of very bright SNe Ia suggest that their progenitor WDs might have a mass which exceeds the Ch-limit ([Garnavich et al., 2007], [Howell et al., 2006], [Scalzo et al., 2010], [Silverman et al., 2011], [Taubenberger et al., 2011], [Yamanaka et al., 2009]).
Some examples of these events are SN 2003fg, SN 2006gz, SN 2007if, SN 2009dc; these SNe Ia require very high mass WD progenitor ($M \approx 2M_{\odot}$) with high amount of produced ^{56}Ni ($M_{^{56}\mathrm{Ni}} \geq 1.4M_{\odot}$).
When a WD accretes mass, it also gains angular momentum. Since it involves issues which are not well understood from first principle (i.e. WD internal viscosity profile and configuration and effects of magnetic fields), it has generally not been taken into account as key part of the SNe Ia progenitors problem.
This higher critical mass can in principle challenge both the DD and the SD paths.
Rotation near the center changes the condition required for explosion, increasing the critical mass: when viscosity dominates, the rotation is almost uniform [Piro, 2008] and the increase may be only about 5%, otherwise differential rotation can allow for pressure support near the center and it can push the critical mass to above $2M_{\odot}$ [Di Stefano et al., 2011].
I. Hachisu et al. [Hachisu et al., 2011] proposed a new SD model for SNe Ia progenitors, in which the mass can increase up to $M > 2M_{\odot}$ starting from the initial value of $1M_{\odot}$. The binary evolution of a WD and a massive MS star goes through three different steps: optically thick winds from the mass-accreting WD [Hachisu et al., 1996], mass-stripping from the binary companion star by the WD winds [Hachisu et al., 2008] and differential rotation which makes possible a WD more massive than the Ch-limit [Yoon and Langer, 2005].
Furthermore, there are three mass-ranges and timescales of exploding WDs depending on secular instability and rotation law (as shown in fig. [2.7]):

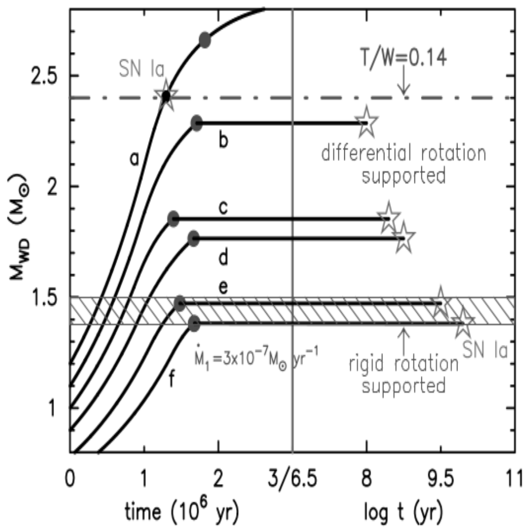


Figure 2.7: Schematic illustration for evolution of the WD mass against time. Time starts when the secondary fills its Roche lobe and it is switched from linear to logarithmic at $t \approx 3 \cdot 10^6$yr (vertical line). The evolutionary lines on the left side are taken from I. Hachisu et al. numerical results while those in the right side are just schematic illustrations [Hachisu et al., 2011].

1. $M > 2.4 M_\odot$: a secular instability sets in at $T = 0.14|W|$ and the WD explodes as SN Ia soon after it exceeds $2.4 M_\odot$ (it corresponds to very luminous super-Ch SNe Ia, such as SN 2007if and SN 2009dc);

2. $1.5 M_\odot \leq M \leq 2.4 M_\odot$ supported by differential rotation;

3. $1.38 M_\odot \leq M \leq 1.5 M_\odot$ supported by rigid rotation.

For $M_{\rm WD} < 2.4 M_\odot$ the WD does not explode soon after it reaches the maximum mass, because the central density is too low and the carbon is not ignited; loss or redistribution of angular momentum would lead to an increase of the central density. [Hachisu et al., 2011].

2.6 SD vs DD in Ch and sub-Ch models: considerations

The SNe Ia progenitors and their evolution to the explosion are not yet well understood. The most accepted models involve a CO-WD which accretes mass in a binary system from a non-degenerate companion star (SD scenario) or through the merger with another WD (DD scenario) until it reaches the Chandrasekhar mass (Ch-models). Even if these proposed systems are theoretically able to produced a SN Ia-like explosion and they are able to reproduce normal SNe Ia features relatively well, they have to face several issues, for example the discrepancies between the SNe Ia rate and the SD or DD progenitors.
Explosion of a WD in a binary system before reaching the Chandrasekhar limit (sub-Ch models), instead, could be a common event since there is the evidence of several sub-Ch mass WDs; moreover it has been demonstrated that also this class of model can, in principle, reproduce the features of normal SNe Ia. However there are several challenges, for example the question of whether such explosions can indeed occur in nature.
Sometimes, the pieces of the SN Ia progenitors puzzle seem to offer a contradictory set of information: as W. Hillebrandt once said “everything taken into account, Type Ia

Supernovae should never take place" (quoted in "*Connecting Recurrent Novae to [some] Type Ia Supernovae*" by F. Patat [Patat et al., 2011]).

2.7 The rates of SNe Ia

Studying the rate of Type Ia Supernovae is important for several reasons: it represents a crucial point to test a model. The rate of SNe Ia critically depends on the distribution of the delay times (DTD), i.e. the time elapsed between the birth of the SN Ia progenitor star and its final explosion. In the current literature, the shape of the DTD is still debated. There are mainly two approaches to derive the DTD:

1. Upon specifications of the distribution of the initial parameters, Binary Population Synthesis (BPS) codes compute the evolution of a population of binaries through the complicated paths (SD and DD in Chandra-channel), determine the partition of the population in the various channels and the delay times of the explosions.

2. An alternative approach to derive the DTD of SN Ia explosions consists in characterizing its shape using general stellar evolution arguments, and introducing a parameterization of a few astrophysical variables believed to play an important role.

2.7.1 Analytic approach to the DTD

In the SD channel, the delay time is very close to the evolutionary lifetime of the secondary star off the MS. If all SNe Ia were arising from this evolutionary path, the range of the secondary star mass should go from $8M_{\odot}$ down to $\leq 1M_{\odot}$, to account for the wide range of delay times implied by SN Ia events happening in all galaxy types [Greggio and Renzini, 1983]; the solid line in fig. [2.8] supports this hypothesis.
(The late epoch steep decline is related to the need of reaching the Ch-mass by summing the WD mass and the envelope of a progressively lower mass donor, which constrains the initial mass of the primary in a progressive narrower range).

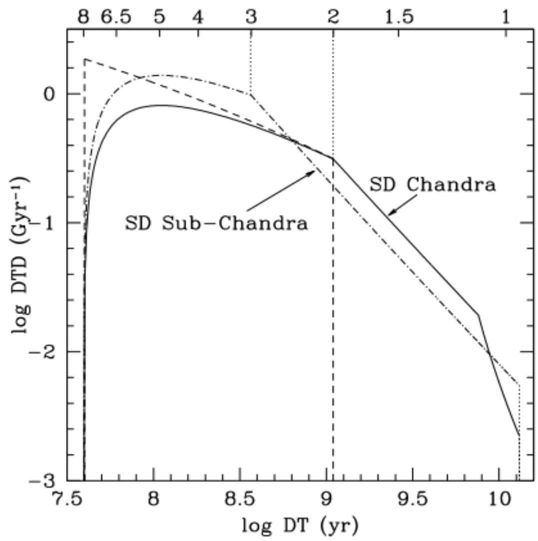


Figure 2.8: Behaviour of the DTD in SD configuration in Ch-model under the assumption of $1-8M_{\odot}$ range (solid line); Behaviour of the DTD in SD configuration in sub-Ch model (dot-dashed line); the dashed line shows the trend of the CO-WD formation rate from the primaries, which may represent un upper limit to the slope of the DTD for the MS + WD channel [Greggio, 2010]

In the DD channel, the delay time is the sum of the MS lifetime of the secondary plus the time taken by the gravitational wave radiation to get the DD system into contact. Analytic distribution of the delay times for the DD channel can be divided into two flavours: the *DD-CLOSE* and the *DD-WIDE* models which refer to two different assumptions for the degree of orbital shrinkage during the first common envelope phase.

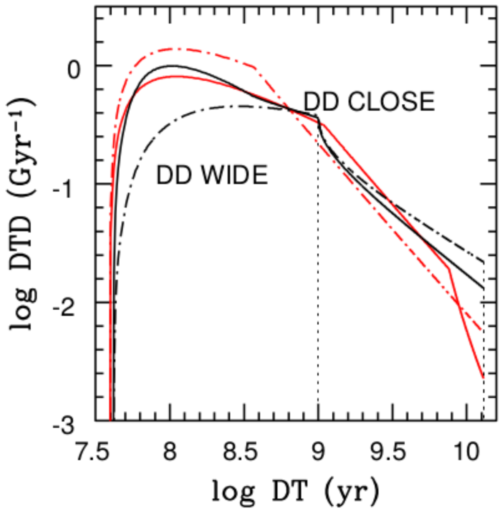


Figure 2.9: Behaviour of the DTD in DD configuration for DD-CLOSE model (solid line) and for DD-WIDE model (dot-dashed line); the DTDs for the SD models are plotted in red for comparison [Greggio, 2010].

The *DD-WIDE* is the least populated at the short delay times, the *DD-CLOSE* the most one (since in this case the time taken by the gravitational wave radiation to get the DD system into contact is short [2.9]).
The comparison of analytic curves with other results in the literature shows that the limits on the component masses play a fundamental role in shaping the DTD, while the effects of the limits on the separation of the primordial binary are less evident (except perhaps for the WD + MS progenitors in SD configuration).
While the analytic DTDs for the DD models match well the BPS results, the DTD of SD models turn out appreciably different.

2.7.2 Effects of parameters

The analytic DTDs have a built-in parameterization of some astrophysical variable related to the binary population and to the progenitor model; in addition, the delay time is related to the exploding system: the variations of SNe Ia progenitor properties with delay time can be figurated.
For the SD model, the curves in the DTD representation depend on the slope of the mass distribution of the primaries, the distribution of the mass ratios, the mass range of the primaries and of the secondaries in successful systems, the accretion efficiency (i.e. the fraction of the envelope mass of the secondary accreted by the primary).
For the DD model, the main parameters which control DTD shape are the maximum delay due to the MS evolution of the secondary, and the shape of the distribution of the separations. Instead, the DTD in DD configuration is not very sensitive to the Initial

Mass Function (IMF) slope and to the distribution of the mass ratios, due to the relatively restricted mass range of the binary components.

2.7.3 Mixed models

The different channels for SN Ia production (SD and DD) are in principle capable to provide both prompt and tardy events; moreover, in both channels, the DTD favours early events, so that the SN Ia rate per unit mass in young stellar systems is expected to be higher than in old ones and each model is compatible with the decreasing rate per unit mass going from late to early-type galaxies [1.1].
Therefore there is no reason to consider the various models as mutually exclusive: both SD and DD paths could well occur in nature and concur to the SN Ia explosion.
Among the many possible combinations for a "mixed model" there are two extreme hypothesis:

1. The Solomonic mix, in which both SD and DD channels contribute half of the total events within $\Delta t = 13\,\text{Gyr}$. The DTD of this mix is similar to each of the SD and DD models; the only characterizing feature is the intermediate slope of the decline at very late delays (due to the contribution of DD channel).

   This kind of mixture and its evolution over cosmic time has been studied in Greggio et al. [Greggio et al., 2008];

2. The Segregated mix, in which the SD explosions provide the early events, while the DD channel provide the late ones. This mix assumes that systems with secondary mass $M_2 \geq 5M_\odot$ feed the SD channel, while systems hosting less massive secondaries undergo CE evolution at the second RLOF to become DD systems and this causes the discontinuity in the DTD at 0.1Gyr.

   This combination is similar to the DTD proposed by Mannucci et al. [Mannucci et al., 2006].

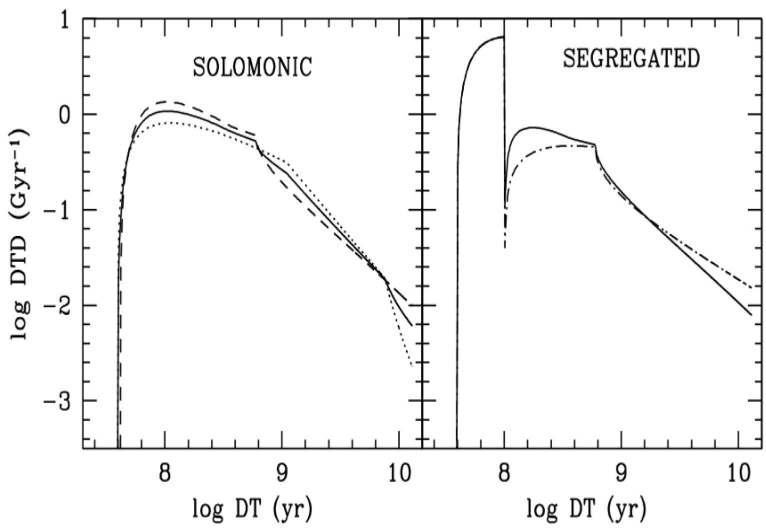


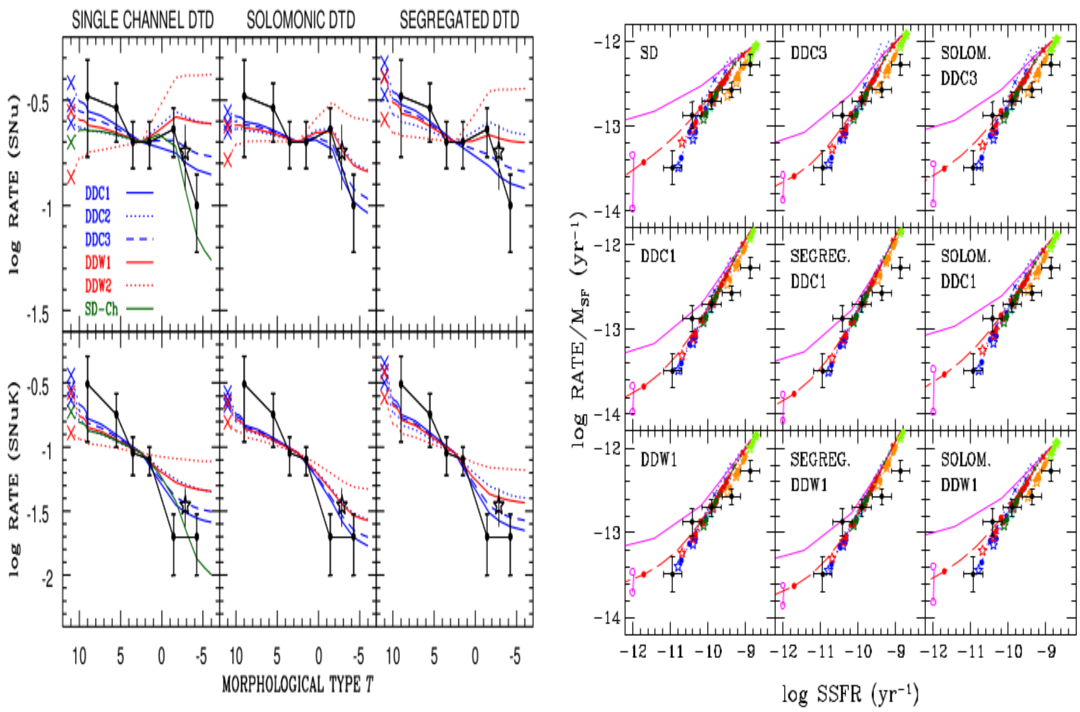
Figure 2.10: DTDs for mixed models: comparison between Solomonic and Segregated mix [Greggio, 2010]

Both the Solomonic and the Segregated mix provide SD and DD explosion in virtually all

galaxy types, but in the very old galaxies (late delay times) almost all events should come from the DD channel; furthermore, this conclusion can be applied only to Ch-models, since sub-Ch events could be common at very late delay times both in SD and in DD paths.
The scaling of SN Ia rate in different stellar systems offers the opportunity of constraining the DTD, hence the SN Ia progenitor model.
Two sets of data can be considered:

1. The relation between the SN Ia rate per unit luminosity and the morphological type of the parent galaxy: this leads to the conclusion that the DTD significantly decreases at very long delay times; the fit obtained by the mixed models is not particularly better than that with single channel models [fig. 2.11];

2. The relation between the SN Ia rate per unit mass and the specific star formation rate (SSFR) of the parent galaxy: this leads to the conclusion that the younger is the galaxy, the higher is SSFR, and its SN Ia rate per unit mass; all DTDs yield an acceptable representation of the data. Anyway, the observed correlation seems to favour SD model or Solomonic mixtures even if no strong conclusion can be drawn. [fig. 2.11]



(a) (b)

Figure 2.11: (i) SN Ia rate per unit B and per unit K luminosity (respectively upper and lower panels), as a function of the morphological type of the parent galaxy; black dots show the observed rates from Greggio & Cappellaro [Greggio and Cappellaro, 2009] [Greggio, 2010]. (ii) Correlation between the SN Ia rate and the SSFR. The data (black dots) are from [Sullivan et al., 2006].

In conclusion, the observed correlations do not clearly favour mixed over single channel models, such as there is no clear theoretical reason neither observed correlations with SSFR and host galaxy type to justify a separate prompt component (Segregated mix). More data are needed to investigate it. [Greggio, 2010]

2.8 Core-Degenerate configuration

An alternative binary system has been presented and analyzed as a different scenario to produce SN Ia explosion: this is called the *core-degenerate* (CD) scenario ([Soker, 2011], [Kashi and Soker, 2011]) and it proposes a system made of a WD and the massive core of an AGB star as SN Ia progenitor.
This merging system was studied in the past ([Sparks and Stecher, 1974], [Livio and Riess, 2003], [Tout et al., 2008]).
Even if this scenario is sometimes presented as a branch of the DD one, N. Soker refers to it as a distinguishable evolutionary path which overcomes some difficulties of the SD and DD scenarios.
Evidences of the possible existence of this kind of channel have been explored, for example, with the analysis of the circumstellar matter of SN 2014J: it is too massive and its momentum is too large to be accounted for by any but the CD scenario [Soker, 2015].

2.8.1 Evolution of the system in CD scenario

In the core-degenerate scenario the Chandrasekhar or super-Chandrasekhar mass WD is formed at the termination of the CE phase or during the planetary nebula phase, from the merger of a WD companion with the hot core of a massive extreme AGB star (in the range $5 - 8M_{\odot}$). The hot core is now more massive than the companion WD (this represents the first important difference with the DD channel).
Furthermore the merger should occur while the core is still large, hence hot. This limits the merger to occur within 10^5yr after the CE phase (second difference with the DD channel). The WD is then destroyed and accreted onto the more massive core: the outcome is a rapidly-rotating magnetized (commonly super-Ch mass) WD.
The merger remnants can explode only after they lose sufficient angular momentum; the WD is expected to spin-down due to the magneto-dipole radiation torque (MDRT). The spin-down process due to MDRT is commonly used for pulsars; this mechanism was applied to WDs by Benacquista et al. [Benacquista et al., 2003].
In the CD scenario most of the delay between the binary formation time and the explosion is due to the spinning-down time of the merger product via MDRT (while in the DD scenario most of the delay time is the spiraling-in time of the two WDs due to the gravitational wave radiation: this represents the third main difference with DD channel).
The strong magnetic fields required in the present model for the spinning-down mechanism most likely will enforce a rigid rotation within a short timescale. This implies that WDs more massive than $1.48M_{\odot}$ (critical mass of rigid rotating WDs [Yoon and Langer, 2004]) will explode in a relatively short time.
Since the core is more massive than the WD companion, the latter will be destroyed. The CD scenario evolution is shown in fig. [2.12]

2.8.2 CD scenario: strong points

Several properties of the CD scenario make it attractive if compared to the other ones: for example, it overcomes some weaknesses of the DD channel.
There are, at least, three key points:

- *CD and AIC.*

  In a merger process in which the more massive WD is hot, off-center carbon ignition is less likely to occur [Yoon et al., 2007]: it is due to the fact that a hot WD is

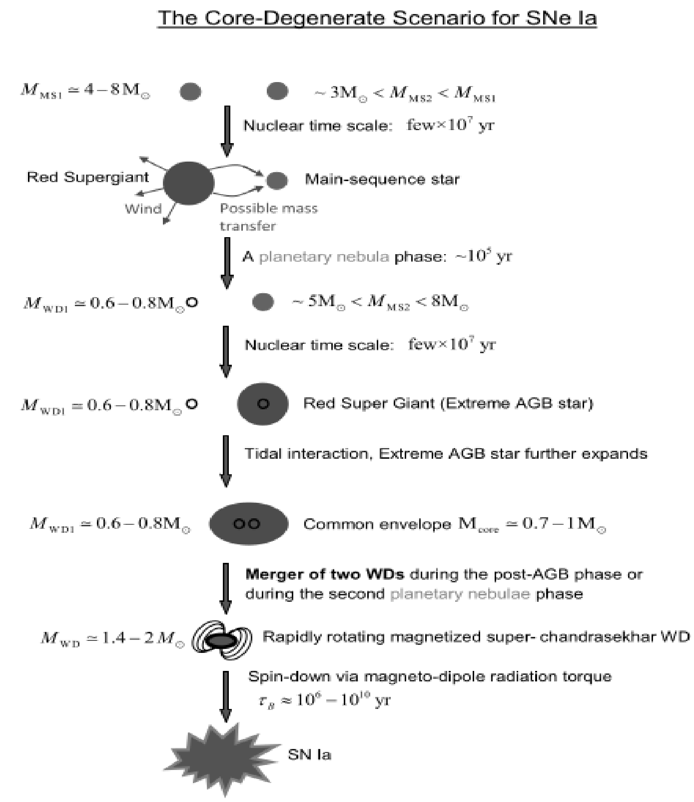


Figure 2.12: A schematic summary of the CD scenario for SNe Ia [Ilkov and Soker, 2011].

larger, the potential well is shallower and the peak temperature of the destroyed WD material is lower; hence, in such a situation the supercritical-mass remnant is more likely to ignite carbon at the center at a later time, leading to a SN Ia explosion.

- *CD and mass loss.*

  In contrast to the DD channel, since in the CD scenario the more massive component is hot (hence its potential well is lower) the core potential and the WD potential are quite the same: it implies that the merger process will not release large amount of energy and no formation of a giant-like structure will take place. The remnant will not have a large radius and no substantial mass loss will occur, thus avoiding the possibility to bring the merger remnant below the critical mass.

- *More luminous SNe Ia in star forming galaxies.*

  The similarity of most SNe Ia suggests that their progenitors indeed come from a narrow mass range. This range is $1.4 - 1.48M_\odot$ for the CD scenario. This property of MDRT spinning-down mechanism, that only WDs with $M_{WD} \leq 1.48M_\odot$ can slow down on a very long timescale, explains the finding that SNe Ia in older populations are less luminous (e.g. [Howell, 2001], [Smith et al., 2011]), and that very massive SN Ia progenitors occur in star forming galaxies (i.e. spirals and irregulars) [Scalzo et al., 2012].

  ([Ilkov and Soker, 2011], [Soker, 2011])

Even if the core-degenerate model has been proposed as a possible solution to some of the questions about the binary systems that lead to SNe Ia, it has to be further studied both observationally (even if the evidence of several super-Ch rapidly rotating WDs does exist) and theoretically: for example it is not completely clear whether the merger remnant, as it spins down, would instead yield a long γ-ray burst (usually associated with type Ib/Ic SNe) and a rapidly spinning magnetar [Tout et al., 2011].

Chapter 3

An alternative channel of evolution towards SNe Ia

E. Chiosi et al. [Chiosi et al., 2015] have recently proposed an alternative possibility to the so far well-known binary channels that are thought to lead to SN Ia explosion: they explore the possibility that isolated CO-WDs with mass smaller than the Ch-limit may undergo a nuclear runaway and SNa explosion due to the energy produced by the underbarrier pycnonuclear reactions between Carbon and light elements (Hydrogen and Helium). These reactions would be due to left over impurities of the light elements which remains inactive until the WDs transit from the liquid to the solid state.
Carbon ignition via pycnonuclear channel is followed by C-detonation or C-deflagration and by a thermal runaway. The liberated nuclear energy exceeds the gravitational binding energy and the star is torn apart.
The pycnonuclear regime starts in very dense and cool environments (i.e. in the liquid-solid state). While the WD radiates, because of high electron degeneracy and the absence of nuclear sources, the ions cool down transiting through gaseous-liquid and eventually solid (crystallized) condition: they form a lattice pervaded by a gas of electrons. At temperature decreasing, the ions reach the fundamental energy state and the Coulombian potential has approximately the form of a harmonic oscillator. From Quantum physics, the energy on the fundamental state is $E = \frac{1}{2}\hbar\omega$ (with ω = plasma frequency), this means that even at low T there's a finite probability for C and O to penetrate the repulsive Coulombian barrier.
The interiors of CO-WDs are made of ions of C, O, traces of other elements and free electrons. Ions are fully ionized and electrons form an uniform background (it's a multi-component plasma, MCP, of ions).
Rates of pycnonuclear reactions between C and O were first calculated by Salpeter & van Horn [Salpeter and Van Horn, 1969] and they first noticed that impurities of light elements may enhance the pycnonuclear reactions among the nuclei of the lattice increasing the nuclear burning rates.

3.1 WD evolution: different burning regimes

During the cooling, the WD undergoes two phase transitions: from gas to liquid and from liquid to solid (crystallization). In parallel to this, there are five burning regimes [Salpeter and Van Horn, 1969]:

1. <u>the classical thermonuclear regime</u> ($\Gamma_{ij} \ll 1$): the nuclei are fully stripped and there

is a small screening effect from the background electron gas. The matter behaves as an ideal gas;

2. The thermonuclear regime with strong electron screening (liquid/lattice phase);

3. the thermonuclear and pycnonuclear regime ($\Gamma_{ij} \geq 1$): nuclei are bound into the lattice sites, so that the reactions occur between highly thermally excited bound nuclei, which oscillate with frequencies higher than the plasma one and have the energy greater than the zero-point energy of the plasma. Nuclei are also embedded in a highly degenerated electron gas;

4. the thermally enhanced pycnonuclear regime ($1 \ll \Gamma_{ij} < 175$): most of the nuclei are bound to the lattice, but some of them are highly excited states and reactions may occur between neighbouring pairs of nuclei. Electron screening is very strong;

5. The pure pycnonuclear regime ($T \approx 0$): almost all the ions are in the fundamental state of the crystallized lattice, but their energies are larger than zero (*Heisenberg indetermination principle*) so there is a finite probability to penetrate the Coulomb barrier (*tunneling effect*). Reactions are possible only between closest pairs.

where $\Gamma_{ij} = \frac{Z_i Z_j e^2}{a_{ij} k_b T}$ (with Z_i, Z_j atomic numbers of ions i, j and a_{ij} the equilibrium distance between neighbouring nuclei) is the Coulomb coupling parameter (the ratio between Coulomb and thermal energy).

3.2 Rates for pycnonuclear reactions

While in the thermonuclear reactions each particle can interact with all the others, in the pycnonuclear ones each nucleus in the lattice can interact only with the nearest neighbours, so the computation of the reaction rates is different.
In literature there are three main different formulations to extimate the pycnonuclear reaction rates: (i) Salpeter & van Horn [Salpeter and Van Horn, 1969], based on the simple harmonic oscillator at zero temperature; (ii) Kitamura [Kitamura, 2000] and (iii) Gasques [Gasques et al., 2005] -Yakovlev [Yakovlev et al., 2006], models that include also the effect of temperature.

3.2.1 Rates in the modified Salpeter-Van Horn model (modified harmonic oscillator model)

The pycnonuclear reactions were studied by Salpeter & van Horn [Salpeter and Van Horn, 1969] who model the pycnonuclear potential with a harmonic oscillator.
Using the same formalism of Shapiro & Teukolsky [Shapiro and Teukolsky, 1983], even if the original theory was developed for reactions among the same nuclei, E. Chiosi et al. [Chiosi et al., 2015] consider an onecomponent plasma (OCP) made of a certain type of ions with charge Z_1 which form the lattice. They substitute the charge Z_1 with the charge Z_2 (in this case light elements: H or He) in a cell. The reaction rate per ion pair is:

$$W = v\left|\Psi_{inc}\right|^2 \frac{TS(E)}{E_k} \tag{3.1}$$

where $\left|\Psi_{inc}\right|^2 \approx \left|\Psi_{SHO}\right|^2 \approx \frac{1}{r_0{}^3\pi^{\frac{3}{2}}}$, S is a slowly varying function of E and

$$T = \exp\left[-2\int_a^b \sqrt{\frac{2\mu}{h^2}(E_0 - V_0 - \frac{1}{2}Kx^2)}\,\mathrm{dx}\right]$$

that is the transmission coefficient for an incident ion with energy E_0 in the Wentzel-Kramers-Brillouin approximation. This is strongly dependent on the charges: infact the exponent is proportional to $\sqrt{Z_1Z_2}$ (since $E, V \propto Z_1Z_2$), and at charge-decreasing (i.e. if we consider $Z_2 < Z_1$) the transmission coefficient becomes much higher, i.e. the reaction is more probable and the rate is higher.
Therefore the presence of impurities of light elements (such as H and He) can theoretically strongly enhance the probability of pycnonuclear reactions occurrence.
In the modified harmonic oscillator (MHO) model it is possible to obtain the energy generation rates for the different reactions ($H +^{12} C$,$^4He +^{12} C$,$^{12}C +^{12} C$) as a function of the central density (since mass and structure of WD depend on it) [fig. 3.1]

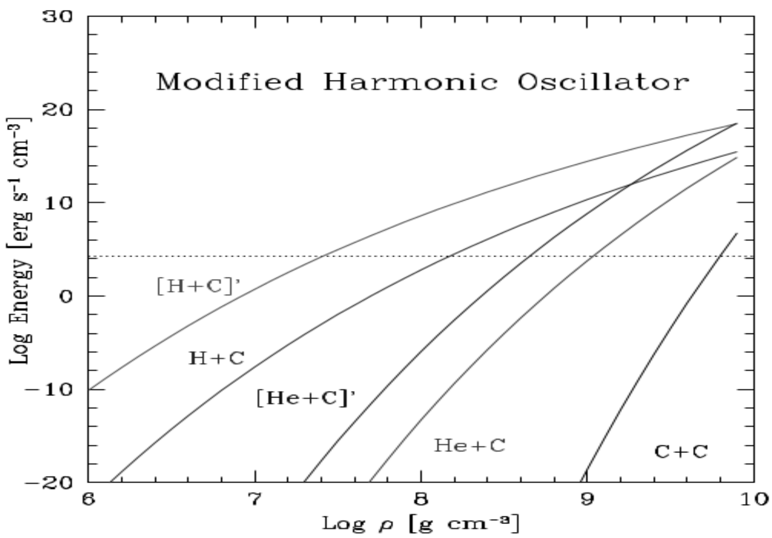


Figure 3.1: The energy generated by the reactions ^1H+^{12}C (H+C), ^4He+^{12}C (He+C), ^{12}C+^{12}C (C+C) according to the MHO rates; the abundances by mass of C, H and He are 10^{-21} and $3{\cdot}10^{-7}$ respectively. The lines [H+C]',[He+C]' correspond to the rate recalculated including the effects of local density caused by the presence of impurities. The dotted horizontal line represents the mean luminosity (in $ergs^{-1}\,cm^{-3}$) of a typical WD ($1.05M_{\odot}$). All the rates intersect the mean luminosity (signature of a potential nuclear runaway) and the intersections occur at higher and higher densities with increasing atomic number [Chiosi et al., 2015]

The result clearly shows that the energy produced by the pycnonuclear reaction between a light element and C at zero T may exceed the typical luminosity of a WD at a density which corresponds to a mass lower than the Chandrasekhar one, while for the reaction $^{12}C +^{12} C$ the correspondent mass is nearly equal to the Chandrasekhar limit.
These are potentially explosive situations.

3.2.2 Kitamura and Yakovlev reaction rates

Kitamura [Kitamura, 2000], Gasques at al. [Gasques et al., 2005] and Yakovlev et al. [Yakovlev et al., 2006] formalisms were originally tailored for reactions like $^{12}C +^{12} C$,

${}^{12}C +^{16} O$, ${}^{16}O +^{16} O$, but they can be extended to reactions involving impurities of light elements and to incorporate the enhancement in the local density.
The models are here used to study the reactions ${}^{1}H +^{12} C$ and ${}^{4}He +^{12} C$.
The results are more general than those of the Salpeter & van Horn [Salpeter and Van Horn, 1969] rates because they also take into account the effects of the temperature, extending from the thermal to the pycnonuclear regime.
The energy generation rate exceeds the mean luminosity of a WD at relatively low densities.

3.3 Traces of H and He in the interior of a WD

From the elementary theory of thermonuclear reactions light elements at very low abundances are expected to be present even after the nuclear phase in which they are burned into heavier species.
In order to have an estimation of the abundances left from the nuclear burnings along the evolutionary history from the zero-age MS to the begin of the thermally pulsating AGB (TP-AGB) phase which terminates with a CO-WD, E. Chiosi et al. [Chiosi et al., 2015] consider the evolutionary sequence of $3,5M_{\odot} - 6M_{\odot}$ stars with solar-like composition (that are the progenitors of massive CO-WDs), and take into account only the nuclear burning occurring in the core; furthermore in these stars H burns via the CNO-cycle with a small contribution of the pp-chain, and He burns via the 3α-process; finally, in first approximation, the nuclear burnings occur only in radiative conditions.
An estimation of the abundances under these conditions can be given in two ways:

- Analytically: considering the relative weight of pp-chain and CNO-cycle in the H-burning process;

- Numerically: considering that in principle the pp-chain and CNO-cycle can occur simultaneously with different efficiency and taking into consideration the structure of the stars during their evolutionary history.

The results of the two models at different stages of evolution are reported in the table (fig. [3.2]):
The results of the numerical model are more reliable because they are tightly related to detailed stellar models. Finally, considering that part of the luminosity at the beginning of the WD cooling may still due, beyond the CNO burning on the surface, also to minor nuclear burning in the interior, thus possibly further lowering the inner content of H, the new abundances are $X_H = 10^{-19} \div 10^{-18}$ and $X_{He} = 10^{-7}$.
Taking into account the real evolution of a WD (therefore the luminosity is no longer constant) and including all energy sources (i.e. the generation by any of the five possible regimes for the pycnonuclear reactions and the thermal energy of the ions), since the abundances of X_H cannot be assessed a priori, it is safe to consider them as a free parameters whose values fall within a plausible range bounded by:

- the maximum: above which the energy production exceeds the WD luminosity during the early stage of the thermally enhanced regime;

- the minimum: below which the energy production equals the WD luminosity at ages older than the age of universe.

Mass	Phase	X_H Analytical	X_H Numerical
3 $M_\odot$	Hb	2.9×10^{-4}	1.7×10^{-7}
	Heb	3.6×10^{-9}	1.3×10^{-14}
	AGB	2.4×10^{-13}	3.3×10^{-18}
5 $M_\odot$	Hb	8.8×10^{-5}	2.4×10^{-7}
	Heb	2.7×10^{-9}	4.2×10^{-14}
	AGB	1.2×10^{-12}	7.8×10^{-18}
6 $M_\odot$	Hb	3.7×10^{-5}	2.8×10^{-7}
	Heb	2.2×10^{-9}	7.3×10^{-14}
	AGB	1.9×10^{-12}	1.2×10^{-17}

Figure 3.2: H-abundances in the innermost regions at the end of the MS (Hb), at the end of core He-burning (Heb) and at the beginning of the TP-AGB phase according to analytical and numerical models [Chiosi et al., 2015].

Considering, for example, the evolution of a 1.2 $M_\odot$ WD at the beginning of the cooling sequence, X_H cannot exceed 10^{-21}, otherwise the nuclear energy released by the sole $^{12}C(^1H, \gamma)^{13}N$ reaction (one of the three starting reactions of the CNO-cycle) during the initial stages of WD cooling is comparable to or even exceeds the total luminosity, thus bringing the WD to a risky regime at which a nuclear runaway may start.
As cooling proceeds, the energy generation by nuclear reactions in the thermally enhanced regime decreases and the light contaminants do not have any effect until the pure pycnonuclear channel begins. In fig. [3.3] the energy production for different H-abundances is plotted as a function of the age of a WD of a given mass in the range $(0.6 - 1.2M_\odot)$.

3.4 A fuse for carbon-ignition

The final question is whether or not a WD containing traces of light elements produces enough nuclear energy via $^1H +^{12} C$ reaction to exceed the WD luminosity. A fraction of this energy would be kept inside the WD creating the physical condition for [C+C]-burning, and likely initiating a nuclear runaway followed by explosion.
How to reach the limit for [C+C]-ignition? E.Chiosi et al. have proposed an alternative way to the Nomoto [Nomoto, 1982] and Kitamura [Kitamura, 2000] ones. A single $^1H+^{12}C$ reaction occurs in a medium in which C and O nuclei are in partially or fully crystallized conditions (i.e. reduced mobility). Consequently the produced energy will be given to the neighbouring nuclei and then shared in a wider environment by conduction and radiation (in WD physical conditions thermal conduction dominates over radiative transport).
Given the mean free path for thermal conduction $\lambda = \frac{1}{k\rho}$ where k is the conductive opacity and ρ the density, in this scenario, it is plausible to conceive that most of the energy emitted by a single [H+C]-reaction is acquired by the nuclei contained in a small volume, approximately a cube of edge λ centered on the H-nucleus. This volume is named elementary burning cell.
Calculating the amount of energy to be shared per unit mass in the cell λ^3 and multiplying

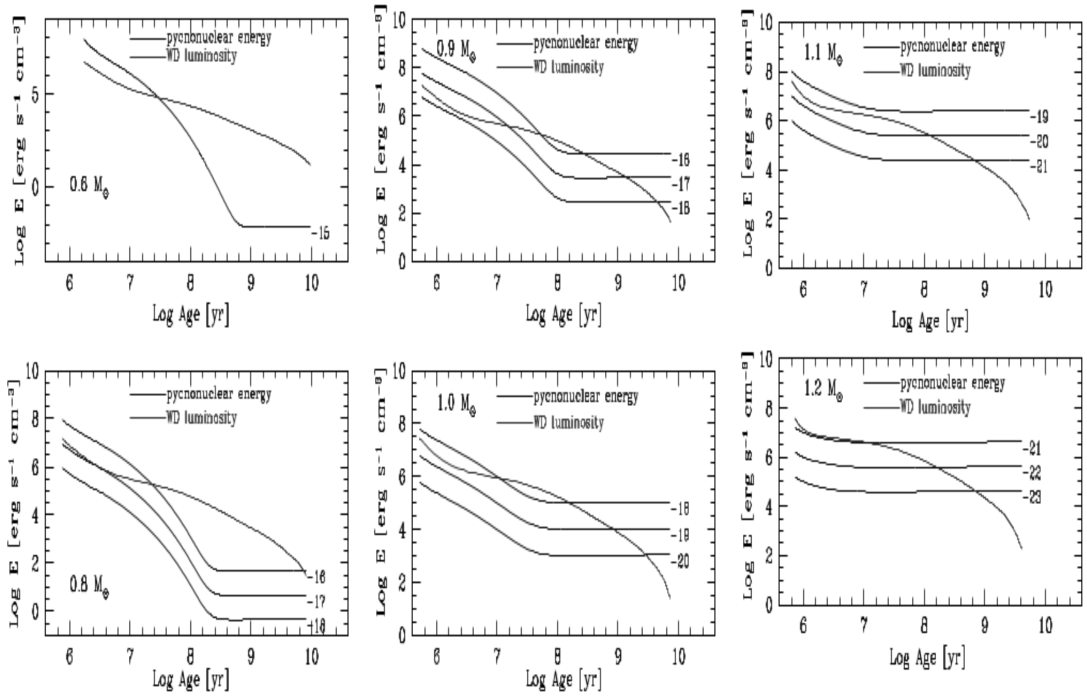


Figure 3.3: Energy rates per unit volume produced by H impurities (with different of X_H) for WDs of different mass; the luminosity is in the same units as the energy generation [Chiosi et al., 2015].

this quantity by the total rate R (in $n\, cm^{-3}\, s^{-1}$) of the [H+C]-reactions the total energy to be shared can be obtained.
It can be shown that the energy deposited by a single [H+C]-reaction, when trapped into the elementary cell, is sufficient to heat and finally ignite the C-nuclei inside the cell.
In order to start C-burning two conditions must be simultaneously satisfied:

- the nuclear energy generation rate per unit volume must overcome the WD luminosity per unit volume, $\varepsilon > \frac{L_{WD}}{V}$;

- the energy input by the [H+C]-reaction to the elementary cell, $[\frac{\varepsilon_\lambda}{\rho}]$, i.e. the energy per unit gram and per unit volume (where $\varepsilon_\lambda = \frac{\varepsilon \cdot 1 cm^3}{\lambda^3}$), must fall below the threshold value for C-ignition $\varepsilon_{CC} = 100\ \frac{erg}{g\, s}$.

Considering three free parameters X_H,τ_1 (the age at which condition (a) is satisfied), τ_2 (the age at which condition (b) is satisfied for the first time), an explosion may only occur at $\tau_1 \leq \tau_2$, as illustrated in fig. [3.4].
From fig. [3.4] a limit to the WD mass can be derived: the condition $\tau_1 \leq \tau_2$ can be met by WD with 0.85 $M_\odot$, 0.9 $M_\odot$, 1.0 $M_\odot$, 1.1 $M_\odot$, 1.2 $M_\odot$ and finally by 0.8 $M_\odot$ as a border line. The two steps [H+C]-reaction and C-ignition are named "*fuse for C-ignition*". Once the fuse is activated, the additional release of energy by C-burning makes it even stronger, propagating it to neighbouring regions, and activating complete C-burning that gradually moves into the thermally driven regime.

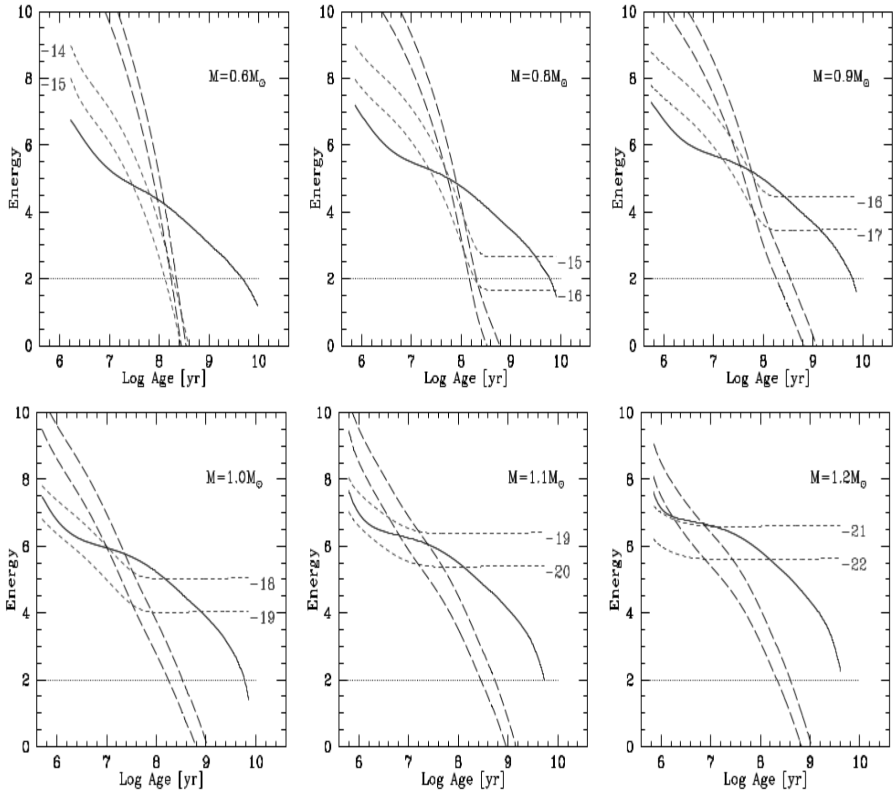


Figure 3.4: The WD luminosity per unit volume (thick solid line), the energy per unit volume produced by the [H+C]-reaction for two values of X_H (thin short-dashed lines), the energy acquired by a typical burning cell for the same values of X_H (thin long-dashed lines) and the threshold value ε_{CC} (horizontal dotted line), all of which are plotted as a function of the logarithm of the age in years. The various energies are plotted on the same logarithmic scale [Chiosi et al., 2015].

3.5 Conclusions

In this discussion a new channel towards SNe Ia has been proposed: an isolated WD with mass below the Ch-limit may reach the threshold for pycnonuclear reactions (and consequent SNa explosion) due to the left traces of light elements. These impurities remain inactive for long periods of time and they are activated only when the WD reaches the liquid/solid regime.
This new semi-analytical model presents several advantages, for example it shows a significant rate of non-Chandrasekhar-mass progenitors or it shows that a single CO-WD may reach the explosion stage soon after the formation if sufficiently massive ($\geq 1.0 M_{\odot}$) and sufficiently rich in residual hydrogen ($X_H = 10^{-19} \div 10^{-20}$).
On the other hand, there is also some shortcoming, as the fact that the success of the model relies on the existence of traces of light elements (complete stellar models in which the abundances of elements are followed are not presently available). Only complete self-consistent models would allow us to have more precise calculations, correctly determining the amount of energy generated by nuclear reactions, and to deal with the energy transport problem, rigorously comparing production versus transport energy. Furthermore, after the WD cools to the temperature for the activation of the underbarrier channel, the explosion as Type Ia SNa is however just one of the possibilities. If the results of this project are confirmed by further investigations, important implications for the currently accepted SN Ia scenario will follow: the binary origin of SN Ia explosion would be no longer necessary. [Chiosi et al., 2015].

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