Type Ia Supernovae and their implications for cosmology

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Models for Type Ia Supernovae (SNe Ia) are reviewed. It is shown that there are strong reasons to believe that most SNe Ia represent thermonuclear disruptions of C–O white dwarfs, when these white dwarfs reach the Chandrasekhar limit and ignite carbon at their centers.

Different progenitor scenarios are reviewed critically and the strengths and weaknesses of each scenario are presented in detail. It is argued that theoretical considerations currently favor single-degenerate models, in which the white dwarf accretes from a subgiant or giant companion. However, it is still possible that more than one progenitor class contributes to the observed sample. The relation of the different models to the use of SNe Ia for the determination of cosmological parameters is discussed. It is shown that while the observed diversity of SNe Ia may argue for the existence of different progenitor classes, this does not affect the interpretation of an accelerating expansion of the universe.

Crucial observational tests of the conclusions are suggested.

1. Introduction

During the past three years two groups (Perlmutter et al. 1997; Schmidt et al. 1998) have presented strong evidence that the expansion of the universe is accelerating rather than decelerating (Riess et al. 1998; Perlmutter et al. 1998, 1999; and see Livio 1999 for a perspective). This surprising result comes from distance measurements to more than fifty supernovae Type Ia in the redshift range $z = 0.1$ to $z = 1$. The results are consistent with the cosmological constant (or vacuum energy) contributing to the total energy density about 60–70% of the critical density, which in turn, is consistent with recent measurements of the anisotropy of the cosmic microwave background (e.g. Miller et al. 1999; Wilson et al. 1999; Mauersperg et al. 1999).

This unexpected finding, as well as the use of supernovae Type Ia to measure the Hubble constant (e.g. Sandage et al. 1996; Saha et al. 1997), have focused the attention again on the frustrating fact that in spite of decades of research, the exact nature of the progenitors of supernovae Type Ia remains unknown. Until this problem is solved, one cannot be fully confident that supernovae at higher redshifts are not somehow different from their low redshift counterparts. In the present review I therefore examine critically models for supernovae Type Ia and their progenitors. Other recent reviews include Branch et al. (1995), Livio (1996a; 2000), Renzini (1996), Iben (1997), and see Höflich & Domínguez, these proceedings.

2. SNe Ia characteristics and the basic model

The defining characteristics of supernovae Type Ia (SNe Ia) are both spectral: (i) the lack of lines of hydrogen, and (ii) the presence of a strong red Si II absorption feature ($\lambda 6355$ shifted to $\sim 6100 \text{ Å}$).

Once defined as SNe Ia, the following are several of the important observational characteristics of the class which may help in the search for progenitors:
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(1) Homogeneity: Until very recently, it has generally been claimed that more than 80% of all SNe Ia form a homogeneous class (see however (2) below) in terms of their spectra (e.g. Branch, Fisher, & Nugent 1993), light curves, and peak absolute magnitudes. The latter are given by

\[ M_B \simeq M_V \simeq -19.30(\pm 0.03) + 5 \log(H_0/60 \text{ km s}^{-1}\text{ Mpc}^{-1}) \quad (2.1) \]

with a dispersion of \( \sigma(M_B) \sim \sigma(M_V) \sim 0.2-0.3 \) (Hamuy et al. 1996a; Tammann & Sandage 1995; and see Branch 1998 for a review).

(2) Inhomogeneity: Some differences in the spectra and light curves have been known to exist for a while (e.g. Hamuy et al. 1996b). In terms of explosion strength, SNe Ia have traditionally been roughly ordered as follows: SNe Ia like SN 1991bg and SN 1992K represent the weakest events, followed by weak events like 1986G, followed by about 80% of all SNe Ia which are called “normals” (or sometimes “Branch normals”), to the stronger than normal events like SN 1991T. In a very recent work, however, Li et al. (2000) find indications for a considerably higher peculiarity rate, a total of \( (39 \pm 10)\% \); of which \( (19 \pm 7)\% \) and \( (21 \pm 7)\% \) are SN 1991bg-like and SN 1991T-like objects respectively.

(3) The luminosity function of SNe Ia was found in earlier studies to decline very steeply on the bright side (e.g. Vaughan et al. 1995). Since selection effects cannot prevent the discovery of SNe which are brighter than the “normals” (unless they occur preferentially in high extinction regions), this is usually taken to imply that the normals are essentially the brightest. The recent study of Li et al. (2000) seems to show, however, that the luminosity function is relatively flat at both the overluminous and underluminous ends.

(4) Near maximum light, the spectra are characterized by high velocity (8000–30,000 km s\(^{-1}\)) intermediate mass elements (O–Ca). In the late, nebular phase, the spectra are dominated by forbidden lines of iron (e.g. Kirshner et al. 1993; Wheeler et al. 1995; Ruiz-Lapuente et al. 1995; Gómez et al. 1996; Filippenko 1997).

(5) Fairly young populations appear to be very efficient at producing SNe Ia (e.g. they tend to be associated with spiral arms in spirals; Della Valle & Livio 1994; Bartunov, Tsvetkov & Filimonova 1994), but relatively old populations (\( \tau \gtrsim 4 \times 10^9 \text{ yr} \)) can also produce them. In particular, SNe Ia do occur in ellipticals (e.g. Turatto, Cappellaro & Benetti 1994). In fact, the rates of SNe Ia in ellipticals appear to be similar to those in spirals, \( \sim 0.188 N_u \) (where \( N_u = 15N(100 \text{ yr})^{-1} \left(10^{10} L_\odot^B\right)^{-1} \); Turatto, Cappellaro & Petroian 1999). This immediately implies that SNe Ia are not caused by the core collapse of stars more massive than 8 \( M_\odot \).

(6) There exist a number of correlations between different pairs of observables (see e.g. Branch 1998 for a review). Of these, the most frequently used in the context of determinations of cosmological parameters is the correlation between the absolute magnitude and the shape of the light curve. Basically, brighter SNe Ia decline more slowly. A parameter commonly used to quantify the light curve shape is \( \Delta m_{15} \) (Phillips 1993), the decline in magnitudes in the \( B \) band during the first 15 days after maximum light. Hamuy et al. (1996a) find slopes \( dM_B/d\Delta m_{15} = 0.78 \pm 0.17, \quad dM_V/d\Delta m_{15} = 0.71 \pm 0.14, \quad \) and \( dM_I/d\Delta m_{15} = 0.58 \pm 0.13. \) Using a stretch-factor \( s \) (Perlmutter et al. 1997), one can write \( M_B = M_B(s = 1) - \alpha(s - 1), \) with \( M_B(s = 1) = -19.46 \) (e.g. Sandage et al. 1996), and \( \alpha = 1.74 \) (Perlmutter et al. 1999). Sophisticated techniques for using the different correlations in distance determinations have been developed (e.g. Riess et al. 1996, 1998).

The above characteristics can be augmented by the following suggestive facts:

(1) The energy per unit mass, \( 1/2(\sim 10^4 \text{ km s}^{-1})^2, \) is of the order of the one obtained from the conversion of carbon and oxygen to iron.
The fact that the event is explosive suggests that degeneracy may play a role.

The spectrum appears to contain no hydrogen.

The explosions can occur with long delays, after the cessation of star formation.

All the properties above have led to one agreed upon model: SNe Ia represent thermonuclear disruptions of mass accreting white dwarfs.

It is interesting that there exists a unanimous consensus on this model in spite of the fact that the essence of flame physics, burning front propagation, and the details of the (presumed) transition from deflagration to detonation (in particular the density at which the transition occurs), which are at the heart of the model, remain as major unsolved problems (e.g. Khokhlov, Oran & Wheeler 1997; Woosley 1997; Reinecke, Hillebrandt & Niemeyer 1998; and see Höflich & Dominguez, and Khokhlov, these proceedings). In fact, given these uncertainties, it is almost difficult to understand how the entire family of SNe Ia light curves can be fitted essentially with one parameter (e.g. Perlmutter et al. 1997), although it is possible that all SNe Ia explode at the same WD mass (see §4), and that the entire observed diversity stems from different \(^{56}\text{Ni}\) masses.

### 3. Why is identifying the progenitors important?

The fact that we do not know yet what are the progenitor systems of some of the most dramatic explosions in the universe has become a major embarrassment and one of the key unsolved problems in stellar and binary star evolution. There are several important reasons why identifying the progenitors has become more crucial than ever:

(i) The use of SNe Ia as one of the main ways to determine key cosmological parameters like \(H_0\), and the contributions to the energy density (by matter and by the cosmological constant) \(\Omega_M\), \(\Omega_\Lambda\) requires an understanding of the evolution of the luminosity, and the SN rate with cosmic epoch. Both of these depend directly on the nature of the progenitors.

(ii) Galaxy evolution depends on the radiative, kinetic energy, and nucleosynthetic output of SNe Ia (e.g. Kauffmann, White & Guiderdoni 1993).

(iii) Due to the uncertainties that still exist in the explosion mechanism itself, a knowledge of the initial conditions and of the distribution of matter in the environment of the exploding star are essential for the understanding of the explosion.

(iv) An unambiguous identification of the progenitors, coupled with observationally determined SNe Ia rates can help to place meaningful constraints on the theory of binary star evolution (e.g. Livio 1996b; Li & van den Heuvel 1997; Yungelson & Livio 1998; Hachisu, Kato & Nomoto 1999). In particular, a semi-empirical determination of the elusive common-envelope-ejection efficiency parameter, \(\alpha_{CE}\), may be possible (e.g. Iben & Livio 1993).

### 4. Refinements to the basic model

The basic model for SNe Ia (that essentially all researchers in the field agree upon) is that of a thermonuclear disruption of an accreting white dwarf (WD). However, additional refinements to the model are possible on the basis of existing observational data and theoretical models. These refinements still do not involve the question of the progenitor systems. Rather, they address the question of the WD composition, and of its mass at the instant of explosion.
4.1. The composition of the exploding WD

In principle, the WD that accretes to the point of explosion could be composed of He, of C–O, or of O–Ne. Let us examine these possibilities one by one.

(i) He WDs: Helium WDs have typical masses that are smaller than \( \sim 0.45 \, M_\odot \) (e.g. Iben & Tutukov 1985). While if accreting, these He WDs can explode following central He ignition at \( \sim 0.7 \, M_\odot \), the composition of the ejected matter in this case will be that of He, \(^{56}\text{Ni}\) and decay products (e.g. Nomoto & Sugimoto 1977; Woosley, Taam & Weaver 1986). This is entirely inconsistent with observations (observational characteristic (4) in §2). Therefore, He WDs certainly do not produce the bulk of SNe Ia.

(ii) O–Ne WDs: Oxygen–Neon WDs form in binaries from main sequence stars of \( \sim 10 \, M_\odot \), although the precise range which allows formation is somewhat uncertain (e.g. Iben & Tutukov 1985; Canal, Isern & Labay 1990; Dominguez, Tornambé & Isern 1993). These systems are probably not numerous enough to constitute the main channel of SNe Ia (e.g. Livio & Truran 1992; Livio 1993). It is also generally expected that O–Ne WDs that manage to accrete enough material to reach the Chandrasekhar limit will produce (via electron capture) preferentially accretion-induced collapses (to form neutron stars) rather than SNe Ia (e.g. Nomoto & Kondo 1991; Gutierrez et al. 1996). Accretion induced collapses do not eject enough nickel to match the light curves of normal SNe Ia, although they may be able to explain very subluminous events like SN 1991bg (e.g. Fryer et al. 1999). I should note that the existing calculations have been performed for WDs of O–Ne–Mg composition, while some recent calculations of the evolution of a 10 \( M_\odot \) star produce degenerate cores which are almost devoid of magnesium (Ritossa, Garcia-Berro & Iben 1996). Nevertheless, because of the above two points it is unlikely that O–Ne WDs produce the bulk of SNe Ia.

(iii) C–O WDs: Carbon–Oxygen WDs are formed in binaries from main sequence stars of up to \( \sim 10 \, M_\odot \). They are therefore both relatively numerous, and they provide a significant “phase space volume” (masses in the range 0.8–1.2 \( M_\odot \); accretion rates in the range \( 10^{-8}–10^{-6} \, M_\odot/\text{yr} \)) in which they are expected to produce SNe Ia (upon reaching the Chandrasekhar limit; e.g. Nomoto & Kondo 1991). Consequently, the accreting WDs that produce most of the SNe Ia are very probably of C–O composition!

4.2. At what mass does the WD explode and where and in what fuel does the ignition take place?

While there is virtually unanimous agreement about everything I said up to now, namely, that: SNe Ia are thermonuclear disruptions of accreting C–O WDs, the next step in the refinement to the model is more controversial. Two major classes of models have been considered, and they suggest entirely different answers to the questions posed by the title of this subsection. In one class, the WD explodes upon reaching the Chandrasekhar mass, as carbon ignites at its center. In the second, the WD explodes at a sub-Chandrasekhar mass, as helium ignites off-center. I will now review briefly each of these classes and point out their strengths and weaknesses.

4.2.1. Chandrasekhar mass carbon ignitors

In this model, considered ‘standard,’ the WD accretes until it approaches the Chandrasekhar mass. Carbon ignition (triggered by compressional heating) occurs at or very near the center and the burning front propagates outwards. Three types of flame propagation models have been considered in the past three decades: (i) detonation (e.g. Arnett 1969; Hansen & Wheeler 1969), (ii) deflagration (e.g. Nomoto, Sugimoto & Neo 1976) and iii) delayed detonation, in which the flame starts as a deflagration which transitions into a detonation at some transition density (e.g. Khokhlov 1991; Woosley & Weaver.
Models of the latter two types ((iii) in particular) have generally been quite successful in explaining the observations (see e.g. Höflich & Dominguez, these proceedings). The main strengths of this model (central carbon ignition at the Chandrasekhar mass) are (see e.g. Höflich & Khokhlov 1996; Nugent et al. 1997; Höflich & Dominguez these proceedings, for detailed modeling):

1. Some $10^{51}$ ergs of kinetic energy are deposited into the ejecta by nuclear energy.
2. $^{56}$Ni decay powers the lightcurve.
3. The density and composition as a function of the ejection of velocity ($X_i(V_{ej})$) are consistent with the observed spectra.
4. The fact that the explosion occurs at the Chandrasekhar mass may explain the broad-brush homogeneity.
5. Spectra (e.g. of SNe 1994D, 1992A) can be fitted in great detail by theoretical models (e.g. Nugent et al. 1997).

The main weaknesses of the Chandrasekhar mass models are:

1. It has proven more difficult than originally thought for WDs to accrete up to the Chandrasekhar mass in sufficient numbers to account for the SNe Ia rate. The difficulty is associated with mass loss episodes in nova explosions, in helium shell flashes and in massive winds or common envelope phases. I will return to some of these problems when I discuss specific progenitor models.
2. For initial WD masses larger than $\sim 1.2$ M$_\odot$, (which can more easily, in principle, reach the Chandrasekhar mass) accretion-induced collapse is a more likely outcome than a SN Ia (e.g. Nomoto & Kondo 1991).
3. The late-time spectrum ($\sim 300$ days), and in particular the Fe III feature at $\sim 4700$ Å does not agree well with Chandrasekhar mass models (Liu, Jeffrey & Schultz 1998).
4. The ‘standard’ model has some difficulty in reproducing the observed (e.g. Riess et al. 1999a) $\sim 20$ days rise times.

My overall assessment of Chandrasekhar mass models is that the strengths significantly outweigh the weaknesses. The calculations of late-time, nebular spectra involve many uncertainties, and hence I do not regard weakness (3) above as fatal (although clearly more work will be required to explain it away). Both weaknesses (1) and (2) can be overcome if it can be demonstrated that SNe Ia statistics can be reproduced within the uncertainties that still plague the theoretical population synthesis models. As I will show in §5, this appears indeed to be the case. Weakness (4) can be overcome (in principle at least) by lower values of the C/O ratio, or by the presence of a 0.2–0.4 M$_\odot$ envelope (see e.g. Höflich, Wheeler & Thielemann 1998). This suggests to me that this is not a fundamental difficulty for the model.

### 4.2.2. Sub-Chandrasekhar mass helium ignitors

In these models a C–O WD accumulates a helium layer of $\sim 0.15$ M$_\odot$ while the total mass is sub-Chandrasekhar. The helium ignites off-center (at the bottom of the layer), resulting in an event known as “Indirect Double Detonation” (IDD) or “Edge Lit Detonation” (ELD). Basically, one detonation propagates outward (through the helium), while an inward propagating pressure wave compresses the C–O core which ignites off-center, followed by an outward detonation (e.g. Livne 1990; Livne & Glasner 1991; Woosley & Weaver 1994; Livne & Arnett 1995; Höflich & Khokhlov 1996; and Ruiz-Lapuente, talk presented at the Chicago meeting on Type Ia Supernovae: Theory and Cosmology, October 1998).
The main strengths of ELD (sub-Chandrasekhar) models are:

1. It is easier to achieve the required statistics, since less mass needs to be accreted, and the WD does not need to be extremely massive (e.g. Ruiz-Lapuente, Canal & Burkert 1997; Di Stefano et al. 1997; Yungelson & Livio 1998).

2. The late-time spectrum (in particular the Fe III feature at $\sim 4700$ Å) agrees better with ELD models.

3. SNe Ia light curves can be reproduced adequately by ELD models (although the light curves rise somewhat faster than observed, due to $^{56}$Ni heating; Höflich et al. 1997).

The main weaknesses of ELD models are:

1. The spectra that are produced by ELD models generally do not agree with observations (e.g. of SN 1994D; Nugent et al. 1997). In particular, the spectra are very blue (due to heating by radioactive Ni), and are dominated by Ni lines, while not showing a strong Si line. The agreement is somewhat better for the subluminous SNe Ia (e.g. SN 1991bg; Nugent et al. 1997; Ruiz-Lapuente, talk presented at the Chicago meeting on Supernovae, October 1998), but even there it is not very good.

2. The highest velocity ejecta have the wrong composition ($^{56}$Ni and He moving at 11,000 to 14,000 km s$^{-1}$, not intermediate mass elements; also no high velocity C; e.g. Livne & Arnett 1995). This is due to the fact that in these models, essentially by construction, the intermediate mass elements are sandwiched by Ni and He/Ni rich layers, at the inner and outer sides, respectively.

3. Since ELD models allow for a range of WD masses, and since more massive WDs produce brighter SNe, one might expect this model to produce a more gradual decline on the bright side of the luminosity function. While this is in contradiction to the observed sharp decline obtained for some of the earlier samples, it may not be in contradiction with the more recent observations of a relatively flat luminosity function (see §2 characteristic (3)).

My overall assessment of the sub-Chandrasekhar mass model is that the weaknesses (and in particular weaknesses (1) and (2) which appear almost inevitable) greatly outweigh the strengths in terms of this being a model for the bulk of SNe Ia. It is still possible that ELDs may correctly represent some subluminous SNe Ia (e.g. Ruiz-Lapuente, Canal, & Burkert 1997; Pinto, private communication).

4.3. The favored model

On the basis of the above discussion the basic model can now be further refined, and I tentatively conclude that: Most SNe Ia represent thermonuclear disruptions of mass accreting C–O white dwarfs, when these white dwarfs reach the Chandrasekhar limit and ignite carbon at their centers!

5. The two possible scenarios

The next step, in which we search for the progenitor systems of SNe Ia is even more controversial. Two possible scenarios have been proposed: (i) The double-degenerate scenario, in which two CO WDs in a binary system are brought together by the emission of gravitational radiation and coalesce (Webbink 1984; Iben & Tutukov 1984). (ii) The single-degenerate scenario, in which a CO WD accretes hydrogen-rich or helium-rich material from a non-degenerate companion (Whelan & Iben 1973; Nomoto 1982).
In the first scenario the progenitor systems are necessarily binary WD systems in which the total mass exceeds the Chandrasekhar mass, and which have binary periods shorter than about thirteen hours (to allow merger within a Hubble time).

In the second scenario the progenitors could be systems like: (i) Recurrent novae (both of the type in which the WD accretes hydrogen from a giant like T CrB, RS Oph, and of the type in which the WD accretes helium rich material from a subgiant like U Sco, V394 CrA, and Nova LMC 1990#2), (ii) Symbiotic Systems (in which the WD accretes hydrogen-rich material from a low mass red giant or a Mira variable), or (iii) persistent Supersoft X-ray Sources (in which the WD accretes at a high rate $\sim 10^{-7} M_\odot/yr$ from a subgiant companion).

I will now examine the strengths and weaknesses of each one of these scenarios.

5.1. The double-degenerate scenario

There is no question that close binary white dwarf systems in which the total mass exceeds the Chandrasekhar mass are an expected outcome of binary star evolution (e.g. Iben & Tutukov 1984; Iben & Livio 1993). Once the lighter WD (which has a larger radius) fills its Roche lobe, it is entirely dissipated within a few orbital periods, to form a massive disk around the primary (e.g. Rasio & Shapiro 1994; Benz, Thielemann & Hills 1989). The subsequent evolution of the system depends largely on the accretion rate through this disk (e.g. Mochkovitch & Livio 1990; see discussion below).

The main strengths of this scenario are the following:

(1) The absence of hydrogen in the spectrum is naturally explained in a model which involves the merger of two C–O WDs. In fact, if hydrogen is ever detected in the spectrum of a SN Ia, this would deal a fatal blow to this model. Tentative evidence for circumstellar Hα absorption is SN 1990M was presented by Polcaro and Viotti (1991). However, Della Valle, Benetti & Panagia (1996) demonstrated convincingly that the absorption was caused by the parent galaxy, rather than by the SN environment.

(2) In spite of some impressions to the contrary, many double WD systems do exist. In a sample of 153 field WDs and subdwarf B stars, Saffer, Livio & Yungelson (1998) found 18 new double-degenerate candidates. Maxted & Marsh (1999) showed (from a radial velocity survey of 46 WDs) that there is a 95% probability that the fraction of double degenerates among DA WDs lies in the range 0.017–0.19. There are currently eight known systems with orbital periods of less than half a day (and the subdwarf B stars PG 1432+159 and PG 2345+318, with orbital periods of 5.4 hr and 5.8 hr respectively may also have WD companions; Moran et al. 1999). While only one of all of these systems (KPD 0422+5421; Koen, Orosz & Wade (1998)) has a total mass which within the errors could be higher than the Chandrasekhar mass, the sample of confirmed short-period double-degenerates is still smaller than the number predicted to contain a massive system.

(3) Population synthesis calculations predict the right statistics for mergers, about $10^{-3}$ yr$^{-1}$ events for populations that are $\sim 10^8$ yr old and $10^{-4}$ yr$^{-1}$ for populations that are $\sim 10^{10}$ yr old.

(4) Since double WD systems were found to exist, mergers with some “interesting” consequences (either a SN Ia or an accretion-induced collapse) appear inevitable.

(5) The explosion or collapse is expected to occur at (or near) the Chandrasekhar mass, which as I noted in §4.3, I regard as a property of the favored model.

The main weaknesses of the double-degenerate scenario are the following:

(1) There are strong indications that WD mergers may lead to off-center carbon ignition, accompanied by the conversion of the C–O WD to an O–Ne–Mg composition,
followed by an accretion-induced collapse rather than a SN Ia (e.g. Mochkovitch & Livio 1990; Saio & Nomoto 1985, 1998; Woosley & Weaver 1986).

(2) Galactic chemical evolution results, and in particular the behavior of the \([\text{O/Fe}]\) ratio as a function of metallicity \([\text{[Fe/H]}]\) have been claimed to be inconsistent with WD mergers as the mechanism for SNe Ia (Kobayashi et al. 1998).

(3) While the unusually high luminosity of SN 1991T and some of its other features have been tentatively attributed to a super-Chandrasekhar product of the merger of two WDs (Fisher et al. 1999), there is little evidence for example for the presence of unburned carbon (as might be expected from the disk formed in the merger process) in most SNe Ia.

Since we are now getting to the final stages in the identification of the progenitors, it is important to assess critically the severity of the above weaknesses. I will therefore discuss now each one of them in some detail.

5.1.1. Constraints from Galactic chemical evolution

Supernovae Type II (SNe II) are explosions resulting from the core collapse of massive \((\gtrsim 8\, M_\odot)\) stars. These supernovae produce relatively more oxygen and magnesium than iron \((\text{[O/Fe]} > 0)\). On the other hand, SNe Ia produce mostly iron and little oxygen. Generally, the impression is that metal poor stars \((\text{[Fe/H]} \leq -1)\) have a nearly flat relation of \([ \text{O/Fe} ] \) vs. \([ \text{Fe/H} ] \), with a value of \([ \text{O/Fe} ] \sim 0.45\) (e.g. Nissen et al. 1994), while disk stars \((\text{[Fe/H]} \gtrsim -1)\) show a linearly decreasing \([ \text{O/Fe} ] \) with increasing metallicity (e.g. Edvardsson et al. 1993; McWilliam 1997). The “observed” (but see below) break (from flat to linearly decreasing) near \([ \text{Fe/H} ] \sim -1\) is traditionally explained by the fact that the early heavy element production was done exclusively by SNe II, with the break occurring when the larger Fe production by SNe Ia kicks in (e.g. Matteucci & Greggio 1986).

Recently, Kobayashi et al. (1998) performed chemical evolution calculations for both the double-degenerate scenario and for the single-degenerate scenario. For the latter they used two types of progenitor systems: one with a red giant companion and an orbital period of tens to hundreds of days, and the other with a near main sequence companion and a period of a few tenths of a day to a few days.

They obtained for the double-degenerate scenario (for which they took a time delay to the explosion of \(\sim 0.1-0.3\) Gyr) a break at \([ \text{Fe/H} ] \sim -2\). For the single-degenerate scenario (with a delay caused by the main sequence lifetime of \(\gtrsim 1\) Gyr; including metallicity effects), they obtained a break at \([ \text{Fe/H} ] \sim -1\). Kobayashi et al. (1998) thus concluded that the Galactic chemical evolution that results from the double-degenerate scenario is inconsistent with observations.

Personally, I am not too convinced by this apparent discrepancy, since Galactic chemical evolution calculations and observations are notoriously uncertain. For example, a recent determination of \([ \text{Ba/Fe} ] \) as a function of \([ \text{Fe/H} ] \) shows a break near \([ \text{Fe/H} ] \sim -2\), which would be consistent with the double-degenerate scenario prediction (Burris et al. 1999). In addition, recent Keck observations of oxygen in unevolved metal-poor stars appear to show no break in the \([ \text{O/Fe} ] \) vs. \([ \text{Fe/H} ] \) relation. Rather, oxygen is enhanced relative to iron over three orders of magnitude in \([ \text{Fe/H} ] \) in a linear relation (Boesgaard et al. 1999; see also Israeliin, Garcia Lopez & Rebolo 1998). While some reservations about these findings have been raised, in particular, a re-analysis of two of the stars of Israeliin et al. shows \([ \text{O/Fe} ] \) ratios which are discrepant with the results of Israeliin et al. and of Boesgaard et al. (Fulbright & Kraft 1999), this in fact demonstrates the uncertainties involved in such determinations (see also Stephens 2000).
5.1.2. Merger only applicable to relatively rare events?

As I noted above, it has been shown that if SN 1991T is at the same distance as SNe 1981B and 1960F, then its luminosity is too high to be explained in terms of a Chandrasekhar mass ejection (Fisher et al. 1999). Thus, it has been suggested that this SN resulted from the explosion of a super-Chandrasekhar object, indicating perhaps that WD mergers may be responsible for at least some SNe Ia.

However, events like SN 1991T, which seem to be associated with regions of active star formation, represent at most \( \sim 20\% \) of the SNe Ia (Li et al. 2000), and therefore, even if they are the results of mergers this still does not mean that WD mergers are the main class of progenitors of SNe Ia. In addition, it is still far from clear whether mergers can lead to explosions at all (see §5.1.3 below). Incidentally, data for a cepheid distance to NGC 4527 (which will help determine the true intrinsic luminosity of SN 1991T) have been obtained with HST, and the analysis is in progress (Saha et al. 2000).

5.1.3. SN Ia or accretion induced collapse?

Potentially the most serious (and possibly even fatal) weakness of the double-degenerate scenario comes from the fact that some estimates and calculations indicate that the coalescence of two C–O WDs may lead to an accretion-induced collapse rather than to a SN explosion (e.g. Mochkovitch & Livio 1990; Saio & Nomoto 1985, 1998; Kawai, Saio & Nomoto 1987; Timmes, Woosley & Taam 1994; Mochkovitch, Guerrero & Segretain 1997).

The point is the following: once the lighter WD fills its Roche lobe, it is dissipated within a few orbital periods (Benz et al. 1990; Rasio & Shapiro 1995; Guerrero 1994), and it forms a hot thick disk configuration around the more massive white dwarf. This disk is mainly rotationally supported and hence central carbon ignition does not take place immediately, but rather the subsequent evolution depends largely on the rate of angular momentum transport and removal, since they determine the accretion rate onto the primary WD. As long as the accretion rate is higher than about \( \dot{M} \gtrsim 2.7 \times 10^{-6} \, M_\odot \, \text{yr}^{-1} \), carbon is ignited off-center (at the core-disk boundary; this may happen during the merger itself; e.g. Segretain 1994). Under such conditions, the flame was found (in spherically symmetric calculations) to propagate all the way to the center within a few thousand years, thus burning the C–O into an O–Ne–Mg mixture with no explosion (i.e. before carbon is centrally ignited; e.g. Saio & Nomoto 1998). Such configurations are expected to collapse (following electron captures on \(^{24}\text{Mg}\)) to form neutron stars (Nomoto & Kondo 1991; Canal 1997). The main questions are therefore:

(i) What accretion rates can be expected from the initial WD-thick disk configuration?

(ii) May some aspects of the flame propagation be different given the fact that the real problem is three-dimensional while most of the existing calculations were performed using a spherically symmetric code? In particular, could the carbon burning be quenched before the transformation to O–Ne–Mg composition occurs?

(iii) Could the WDs ignite even prior to the merger due to tidal heating, and what would be the outcome of such pre-merger ignition?

The answers to all of these questions involve uncertainties, however some possibilities appear more likely than others. First, it appears very difficult to avoid high accretion rates. If the MHD turbulence that is expected to develop in accretion disks (e.g. Balbus & Hawley 1998) is operative, with a corresponding viscosity parameter of \( \alpha \sim 0.01 \) (where the viscosity is given by \( \nu = \alpha c_s H \), with \( H \) being a vertical scaleheight in the disk and \( c_s \) the speed of sound; e.g. Balbus, Hawley & Stone 1996), then angular momentum can be removed in a matter of days! In such a case, even if the accretion rate is Eddington limited (at \( \sim 10^{-5} \, M_\odot/\text{yr} \)), off-center carbon ignition should still occur, with an eventual
collapse rather than an explosion. Deviations from spherical symmetry can only hurt, since they may allow accretion to proceed at a super-Eddington rate. It is difficult to see why the dynamo-generated viscosity would be suppressed for the kind of shear and temperatures expected in the disk.

Concerning the burning itself, recent attempts at multi-dimensional calculations of the flame propagation and a more detailed analysis of some of the processes involved (Garcia-Senz, Bravo & Serichol 1998; Bravo & Garcia-Senz 1999) indicate that if anything, accretion induced collapses are an even more likely outcome than previously thought. This is due to the effects of electron captures in Nuclear Statistical Equilibrium which tend to stabilize the thermonuclear flame, and to Coulomb corrections to the equation of state. The latter has the effect of reducing the flame velocities and the electronic and ionic pressures, all of which result in a reduction in the critical density which separates explosions from collapses.

As two WDs approach merger, their interiors can be spun up by tidal forces. If these tides can bring (at least one of) the WDs into quasi synchronism between the spin period and the orbital period, high dissipation rates and heating will ensue (Rieutord & Bonazolla 1987). The obtained luminosities due to this tidal heating can reach values as high as \( \gtrsim 10^{37} \) erg s\(^{-1}\) (Rieutord & Bonazolla 1987; Iben, Tutukov & Federova 1998). If such heating indeed occurs, it could have (in principle at least) two important effects: (i) it would increase the probability of detection of pre-merger WDs, due to the increased luminosity and the expected periodic variability (due to mutual occultations), (ii) heating could lead to carbon ignition prior to or during the merger.

¿From the point of view of the present discussion it is important to assess whether the latter possibility makes the merging WDs more viable progenitor systems. This does not appear to be the case for the following reasons:

(i) It is not obvious that a WD can be brought to synchronous rotation. The normal viscosity of WD matter is very low (e.g. Durisen 1973), which can make the viscous timescale even longer than the system’s lifetime. This problem however may be overcome if turbulence develops due to the strong shear.

(ii) It is not clear if carbon will be ignited even if tidal heating occurs. In fact, in the calculations of Iben et al. (1998) carbon failed to be ignited (although only by a relatively narrow margin).

(iii) Even if carbon is ignited, it is very likely that the ignition will occur off-center, making an accretion induced collapse a more likely outcome than a SN Ia (as explained above).

Finally, on the observational side there are also two points which argue at some level against WD mergers as the main SNe Ia progenitors.

(i) Even if MHD viscosity could somehow be suppressed in the disk, and the disk surrounding the primary WD could cool down, so that angular momentum would be transported only via the viscosity of (partially) degenerate electrons, this would result in an accretion timescale of \( \sim 10^9 \) yrs (Mochkovitch & Livio 1990; Mochkovitch et al. 1997). The system prior to the explosion would have an absolute magnitude of \( M_V \leq 10 \) (with much of the emission occurring in the UV). There is no evidence for the existence of some \( \sim 10^7 \) such objects in the Galaxy.

(ii) The existence of planets around the pulsars PSR 1257+12 and PSR 1620–26 (Wolszczan 1997; Backer 1993; Thorsett, Arzoumanian & Taylor 1993) could be taken to mean (this is a model dependent statement) that mergers tend to produce accretion induced collapses rather than SNe Ia. In one of the leading models for the formation of such planets (Podsiadlowski; Pringle & Rees 1991; Livio, Pringle & Saffer 1992), the planets form in the following sequence of events. The lighter WD is dissipated (upon Roche lobe
overflow) to form a disk around the primary. As material from this disk is accreted, matter at the outer edge of the disk has to absorb the angular momentum, thereby expanding the disk to a large radius. The planets form from this disk in the same way that they did in the solar system, while the central object collapses to form a neutron star.

5.1.4. Overall assessment of the double-degenerate scenario

It has now been observationally demonstrated that many double-degenerate systems exist. The general agreement between the distribution of the observed properties (e.g., orbital periods, masses) and those predicted by population synthesis calculations (Saffer, Livio & Yungelson 1998), suggests that the fact that no clear candidate (short period) system with a total mass exceeding the Chandrasekhar mass has been found yet, may merely reflect the insufficient size of the observational sample. Thus, there is very little doubt in my mind that statistics is not a serious problem. The most disturbing uncertainty is related to the outcome of the merger process itself. The discussion in §5.1.3 suggests that collapse to a neutron star is more likely than a SN Ia (see also Mochovitch et al. 1997).

5.2. The single-degenerate scenario

The main strengths of the single degenerate scenario are:

1. A class of objects in which hydrogen is being transferred at such high rates that it burns steadily on the surface of the WD has been identified—the Supersoft X-ray Sources (e.g. Greiner, Hasinger & Kahabka 1991; van den Heuvel et al. 1992; Southwell et al. 1996; Kahabka and van den Heuvel 1997). If the accreted matter can indeed be retained, this provides a natural path to an increase in the WD mass towards the Chandrasekhar mass (e.g. Di Stefano & Rappaport 1994; Livio 1995, 1996a; Yungelson et al. 1996).

2. Other candidate progenitor systems are known to exist, like symbiotic systems (e.g. Munari & Renzini 1992; Kenyon et al. 1993; Hachisu, Kato & Nomoto 1999) and recurrent novae (Hachisu et al. 1999a).

3. There have been claims that the single degenerate scenario fits better the results of Galactic chemical evolution (e.g. Kobayashi et al. 1998). However, as I have shown in §5.1.1, recent observations cast doubt on this assertion. Similarly, nucleosynthesis results show that in order to avoid unacceptably large ratios of $^{54}$Cr/$^{56}$Fe and $^{50}$Ti/$^{56}$Fe, the central density of the WD at the moment of thermonuclear runaway must be lower than $\sim 2 \times 10^9$ g cm$^{-3}$ (Nomoto et al. 1997). Such low densities are realized for high accretion rates ($\gtrsim 10^{-7}$ M$_\odot$ yr$^{-1}$), which are typical for the Supersoft X-ray Sources. Nucleosynthesis results suffer too, however, from considerable uncertainties (e.g. Nagataki, Hashimoto & Sato 1998).

The main weaknesses of the single degenerate scenario are:

1. The upper limits on radio detection of hydrogen at 2 and 6 cm in SN 1986G, taken approximately one week before optical maximum (Eck et al. 1995), rule out a symbiotic system progenitor for this system with a wind mass loss rate of $10^{-7} \lesssim \dot{M}_W \lesssim 10^{-6}$ M$_\odot$ yr$^{-1}$ (Boffi & Branch 1995). This in itself is not fatal, since SN 1986G is somewhat peculiar (e.g. Branch and van den Bergh 1993), and the upper limit on the mass loss rate is at the high end of observed symbiotic winds. An even less stringent upper limit from x-ray and H$\alpha$ observations exists for SN 1994D (Cumming et al. 1996).

2. There exists some uncertainty whether WDs can even reach the Chandrasekhar mass at all by the accretion of hydrogen (e.g. Cassisi, Iben & Tornambe 1998). Furthermore, even if they can, the question of whether they can produce the required SNe Ia
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statistics is highly controversial (e.g. Yungelson et al. 1995, 1996; Yungelson & Livio 1998, 1999; Hachisu, Kato & Nomoto 1999; Hachisu et al. 1999a).

I will now examine these weaknesses in some detail.

5.2.1. Observational detection of hydrogen

Ultimately, the presence or total absence of hydrogen in SNe Ia will distinguish unambiguously between single-degenerate and double-degenerate models. To date, hydrogen has not been convincingly detected in any SN Ia. It is interesting to note that narrow λ6300, λ6363 [O I] lines were observed only in one SN Ia (SN 1937C; Minkowski 1939), but even in that case there was no hint of a narrow Hα line. Hachisu, Kato & Nomoto (1999) estimate in one of their models (which involves stripping of material from the red giant; see below) a density measure of $M/v_{10} \sim 10^{-8} M_\odot$ yr$^{-1}$ (where $v_{10}$ is the wind velocity in units of 10 km s$^{-1}$), while the most stringent radio upper limit existing currently (for SN 1986G) is $M/v_{10} \sim 10^{-7} M_\odot$ yr$^{-1}$ (Eck et al. 1995; for SN 1994D Cumming et al. 1996) find from Hα an upper limit of $M \sim 1.5 \times 10^{-5} M_\odot$ yr$^{-1}$ for a wind speed of 10 km s$^{-1}$; for SN 1992A Schlegel & Petre (1993) find from X-ray observations an upper limit of $M/v_{10} = (2-3) \times 10^{-6} M_\odot$ yr$^{-1}$). Thus, while it is impossible at present to rule out single-degenerate models on the basis of the apparent absence of hydrogen, the hope is that near future observations will be able to determine definitively whether this absence is real or if it merely represents the limitations of existing observations (an improvement by two orders of magnitude in the sensitivity will give a definitive answer).

I should note that a narrow emission feature possibly corresponding to Hα was detected in SN 1981b (in NGC 4536), however no trace of the emission was seen 5 days later (Branch et al. 1983).

5.2.2. Statistics

Growing the WD to the Chandrasekhar mass is not easy. At accretion rates below $\sim 10^{-8}$ M$_\odot$/yr WDs undergo repeated nova outbursts (e.g. Prialnik & Kovetz 1995), in which the WDs lose more mass than they accrete between outbursts (e.g. Livio & Truran 1992). For accretion rates in the range $10^{-8}$–a few $\times 10^{-7}$ M$_\odot$/yr, while helium can accumulate, the WDs experience mass loss due to helium shell flashes and due to the common envelope phase which results from the engulfing of the secondary star in the expanding envelope (with mass loss occurring due to drag energy deposition). At accretion rates above a few $\times 10^{-7}$ M$_\odot$/yr, the WDs expand to red giant configurations and lose mass due to drag in the common envelope and due to winds (e.g. Cassisi et al. 1998). The net result of these constraints has been that population synthesis calculations which follow the evolution of all the binary systems in the Galaxy, tended until recently to conclude that single degenerate channels manage to bring WDs to the Chandrasekhar mass only at about 10% of the inferred SNe Ia frequency of $4 \times 10^{-3}$ yr$^{-1}$ (e.g. Yungelson et al. 1995, 1996; Yungelson & Livio 1998; Di Stefano et al. 1997; although see Li & van den Heuvel 1997).

Very recently, a few serious attempts have been made to investigate whether the statistics could be improved by increasing the “phase space” for single degenerate scenarios, given the fact that population synthesis calculations involve many assumptions. These attempts resulted in the identification of three directions in which the phase space could (potentially) be increased.

(i) The accumulation efficiency of helium has been recalculated using OPAL opacities (Kato & Hachisu 1999). These authors concluded that helium can accumulate much more efficiently than found by Cassisi et al. (1998), mainly because the latter authors used relatively low WD masses (0.516 M$_\odot$ and 0.8 M$_\odot$) and old opacities in their calculations.
(ii) Hachisu et al. (1999a,b) claimed to have identified two evolutionary channels for single-degenerate systems previously overlooked in population synthesis calculations. In the first of these channels, the C–O WD is formed from a red giant with a helium core of 0.8–2.0 M⊙ (rather than from an asymptotic giant branch star with a C–O core). The immediate progenitors in this case are expected to be either helium-rich Supersoft X-ray Sources or recurrent novae of the U Sco subclass (where the accreted material appears to be helium rich).

In the second channel, Hachisu et al. (1999b) considered very wide (initial separations as large as ∼ 40,000 R⊙) symbiotic systems, in which the components are brought together by the inclusion of new physical effects (see (iii)–(3) below).

(iii) It has been suggested that the inclusion of a few additional physical effects, can increase substantially the phase space of the symbiotic channel (Hachisu, Kato & Nomoto 1996, 1999b). These new effects included:

1. The WD loses much of the transferred mass in a massive wind. This has the effect that the mass transfer process is stabilized for a wider range of mass ratios, up to $q_{\text{max}} = m_2/m_1 = 1.15$ instead of $q_{\text{max}} = 0.79$ without the massive wind.

2. It has been suggested that the wind from the WD strips the outer layers of the red giant at a high rate. This increases the allowed mass ratios (for stability) even above 1.15, essentially indefinitely.

3. It has been suggested that at large separations (up to ∼ 40,000 R⊙), when the orbital velocity is of the order of the wind velocity, the wind from the red giant acts like a common envelope to reduce the separation, thus allowing much wider initial separations to result in interaction.

There are many uncertainties associated with all of these attempts to increase the phase space. For example, the efficiency of mass stripping from the giant by the wind from the WD may be much smaller than assumed by Hachisu et al. (1999b), for the following reasons. At high accretion rates, much of the mass loss from the WD may be in the form of an outflow or a collimated jet, perpendicular to the accretion disk rather than in the direction of the giant. Evidence that this is the case is provided by the jet satellite lines to He II 4686, Hβ and Hα observed in the Supersoft X-ray Source RX J0513.9–6951 (Southwell et al. 1996). These jet lines are very similar to those seen in the prototypical jet source SS 433 (e.g. Vermeulen et al. 1992). Furthermore, even if some of the WD wind hits the surface of the giant, it is not clear how efficient it would be in stripping mass, since the rate of energy deposition per unit area by the wind is smaller by two orders of magnitude that the giant’s own intrinsic flux.

Similarly, the efficiency of helium accumulation is still highly uncertain, as the differences between the results of Kato & Hachisu (1999) and Cassisi et al. (1998) have shown.

Also, the particular form of the specific angular momentum in the wind used by Hachisu, Kato & Nomoto (1999b; point (3) above) may be realized only in relatively rare cases (Yungelson & Livio 2000).

Finally, all the new suggestions for the increase in phase space rely very heavily on the results of the wind solutions of Kato (1990; 1991), which involve a treatment of the radiation and hydronamics not nearly as sophisticated as that of more state of the art radiative transfer codes (e.g. Hauschildt et al. 1995, 1996).

5.2.3. Overall assessment of the single-degenerate scenario

The above discussion suggests that probably not all the scenarios for increasing the “phase space” of the single-degenerate channels work (if they did, we might have had the opposite problem of too high a frequency of SNe Ia!). However, these attempts serve
to demonstrate that the input physics to population synthesis codes still involves many uncertainties. My feeling is therefore that given the many potential channels leading to SNe Ia, statistics should not be regarded as a serious problem.

Single-degenerate scenarios therefore appear quite promising, since unlike the situation a decade ago, a class of objects in which the WDs accrete hydrogen steadily (the Supersoft X-Ray Sources) has actually been identified. The main problem with single-degenerate scenarios remains the non-detection of hydrogen so far. While a difficult observational problem (see §6), the establishment of the presence or absence of hydrogen in SNe Ia should become a first priority for SNe observers.

5.3. What if....?  

Given the fact that there are still uncertainties involved in identifying the SNe Ia progenitors, and that WD mergers and some form of off-center helium ignitions almost certainly occur, it is instructive to pose a few “what if” questions. For example: What if WD mergers with a total mass exceeding Chandrasekhar do not produce SNe Ia, what do they produce then? The answer in this case will have to be that they almost certainly produce either neutron stars via accretion induced collapses, or single WDs, if the merger is accompanied by extensive mass loss from the system. Fryer et al. (1999) estimate (from nucleosynthesis constraints) that less than 0.1% of the total Galactic neutron star population is produced via accretion induced collapses.

What if off-center helium ignitions (ELDs) do not produce SNe Ia? In this case, if an explosive event indeed ensues, a population of “super novae” (with \( \sim 0.15 \, M_\odot \) of \(^{56}\)Ni and He) is yet to be detected (maybe SN 1885A in M31 was such an event?). What if off-center helium ignitions do produce SNe Ia? What comes out of the systems with \( M_{\text{WD}} \gtrsim 1 \, M_\odot \), which should be even brighter? If indeed \( \sim 20\% \) of SNe Ia are SN 1991T-like (Li et al. 2000), then maybe these could be represented by such events. This is far from certain, however, since an analysis of the properties of SN 1991T showed that these properties would be very difficult to reproduce even with a nickel mass approaching the Chandrasekhar mass (Fisher et al. 1999). Thus, we see that off-center helium ignitions seem to present an observational problem both if they do and if they do not produce SNe Ia. To me this suggests that the physics of these events is not yet well understood (for example, maybe off-center helium ignition fails to ignite the C–O core after all).

6. How can we hope to unambiguously identify the progenitors?  

There are several ways in which observations of both nearby and distant supernovae could solve the mystery of SNe Ia progenitors:

(1) A combination of early high resolution optical spectroscopy, x-ray observations and radio observations of nearby SNe Ia can both provide limits on \( M/v \) from the progenitors and potentially detect the presence of circumstellar hydrogen (if it exists).

For example, narrow HI in emission or absorption could be detected either very early, or shortly after the ejecta become optically thin (\( \sim 100 \) days). The latter is true because the SN ejecta probably engulfs the companion at early times (e.g. Chugai 1986; Livne, Tuchman & Wheeler 1992). The interaction of the ejecta with the circumstellar medium can be observed either in the radio (e.g. Boffi & Branch 1995) or in x-rays (e.g. Schlegel 1995). The collision of the ejecta (with circumstellar matter) can also set up a forward and a reverse shock (e.g. Chevalier 1984; Fransson, Lundqvist & Chevalier 1996), and radiation from the latter can ionize the wind and produce H\( \alpha \) emission (e.g. Cumming et al. 1996).

(2) Early observations (again of nearby SNe Ia) of the gamma-ray light curve (or
gamma-ray line profiles) could distinguish between carbon ignitors and sub-Chandrasekhar helium ignitor models (see §4.2.2) since the latter can be expected to result in a quicker rise of the gamma-ray light curve due to the presence of $^{56}$Ni in the outer layers (and different gamma-ray line profiles; because of the high velocity $^{56}$Ni).

(3) Another important aspect of the single degenerate scenario which can be tested by observations of both nearby and very distant supernovae is the dependence on metallicity. The increase in the “phase space” of single degenerate progenitors, which is required to make the statistics more compatible with observations (§5.2.2), relies heavily on the existence of an optically thick wind from the WD. For a low metallicity of the accreted matter ([Fe/H] $\lesssim -1$), the wind from the WD is strongly suppressed (since the wind is driven by a peak in the opacity, which is due to iron lines; e.g. Kobayashi et al. 1998). Consequently, it is expected that SNe Ia rates will be significantly lower in low iron abundance environments. Thus, determinations of relative rates in dwarf galaxies (and in the very outskirts of spiral galaxies) can help determine the viability of a key ingredient in the single degenerate scenario.

Similarly, a significant drop may be expected in the rate of SNe Ia at redshift $z \sim 2$ (again due to the decrease in metallicity).

(4) In general, observations of very distant supernovae (at $z \sim 2$–4) with the Next Generation Space Telescope (NGST) can help significantly in identifying the progenitors (e.g. Yungelson & Livio 1999, 2000; Nomoto et al. 2000). For example, the progenitors can be identified from the observed frequency of SNe Ia as a function of redshift (e.g. Yungelson & Livio 1998, 1999, 2000; Ruiz-Lapuente & Canal 1998; Madau, Della Valle & Panagia 1998; Nomoto et al. 2000; and see §8), since different progenitor models produce different redshift distributions. Personally, I think that it would be quite pathetic to have to resort to this possibility. Rather, one would like to be able to identify the progenitors independently, and then use the observations of supernovae at high $z$ to constrain models of cosmic star formation rates, and of cosmic evolution of SNe rates, luminosity, and input into galaxies.

7. Cosmological implications: could we be fooled?

One of the key questions that result from the uncertainties in the theoretical models and the fact that we do not know with certainty which systems are the progenitors of SNe Ia is clearly: is it possible that SNe Ia at higher redshifts are systematically dimmer than their low-redshift counterparts? In this respect it is important to remember that a systematic decrease in the brightness by $\sim 0.25$ magnitudes is sufficient to explain away the need for a cosmological constant. This question became particularly relevant when an analysis of the rise times of SNe Ia (which was based on preliminary estimates for the high-$z$ sample; by Goldhaber 1998 and Groom 1998) seemed to show that high-redshift SNe have shorter rise times by 2.5 days than the low-$z$ SNe (Riess et al. 1999b). A more recent analysis (which used more realistic error estimates than those used by Goldhaber 1998), however, found a better agreement (within $2\sigma$) between the rise times of the low- and high-redshift SNe Ia (Aldering, Knop & Nugent 2000).

In a recent work, Yungelson & Livio (1999) calculated the expected ratio of the rate of SNe Ia to the rate of SNe from massive stars (Types II, Ia, Ic) as a function of redshift for several progenitor models. The possibility of having different classes of progenitors contributing to the total SNe Ia rate should definitely be considered, especially in view of the tentative finding by Li et al. (2000) that there is a relatively high rate ($\sim 40\%$) of peculiar SNe Ia among the local sample. If confirmed, these findings suggest that homogeneity should no longer be considered a very strong constraint on progenitor models.
I should note though that diversity among SNe Ia does not necessarily imply different progenitors, since even in the context of one progenitor model diversity may arise for example from changes in the carbon mass fraction of the WD, which in turn may depend on the environment (e.g. Nomoto et al. 2000). Yungelson and Livio (1999) showed (within the uncertainties of population synthesis models) that if different progenitor systems can contribute to the total SNe Ia rate (e.g. double-degenerate and single degenerates), then it is possible, in principle, that one class of progenitors (e.g. double degenerates) will dominate the rates of the local (low-z) sample, while a different progenitor class (e.g. single degenerate) will start to dominate at z \( \lesssim 1 \). This is a consequence of the fact that the SNe Ia rate from double degenerates is expected to decline quite steeply from \( z = 0 \) to \( z \sim 1 \), while the rate from single degenerates is expected to stay relatively flat in this redshift interval. However, at least within the assumptions of their model calculations, it appears that such a transition is not very likely, because of the following reason: If the contribution from physically different channels (like double degenerates and single degenerates, both at the Chandrasekhar mass) was indeed significant, with a transition from dominance by double degenerates to single degenerates occurring at \( z \sim 1 \), one would have expected to observe this division more clearly in the local and distant samples. For example, the local sample should be dominated by the double degenerate progenitors (with a ratio of double to single degenerates which should be consistent with the results of Li et al. 2000). At the same time, however, the high-z \( (z \gtrsim 1) \) sample should be dominated by single degenerates, but with the contributions from the single and double degenerate channels not being vastly different (in particular, the contribution should be equal at the transition point). This is not consistent with the observations of the high-z sample, the latter appearing to be (within the observational uncertainties) very homogeneous (Li et al. 2000). Consequently, I do not think it likely that the observed universal acceleration is an artifact of the observed SNe Ia sample being dominated by different progenitor classes at high- and low-z (this view is supported by the measurements of the anisotropy of the microwave background).

I should note that the most surprising aspect in the results of Li et al. (2000) is the fact that although very bright SNe Ia (SN 1991T-like) constitute \((21 \pm 7)\%\) of the local sample, these bright objects appear to be totally absent from the high-z sample. One way in which one could (in principle) explain this fact is the following. Suppose that the SN 1991T-like events are caused by mergers (since a super-Chandrasekhar mass is possible in this case), while the “normals” are caused by single degenerates. In this case the local sample would be dominated by single degenerates \((\sim 60\% \) of the events to agree with Li et al., 2000), while double degenerates would contribute \(\sim 20\%\) of the events (I ignore here the weak events since they cannot be seen at high-z). Now, since the rate of events from single degenerates stays quite flat till \( z \sim 1 \), while the rate of events from double degenerates declines quite steeply towards \( z \sim 1 \), the bright objects will be missing from the high-z sample. Note, however, that this potential explanation for the behavior of the diversity has no obvious implications for the finding of accelerating expansion, since the same class of progenitors dominates both the high-z and low-z samples. Nevertheless, a better understanding of the apparent diversity at low-z and apparent lack thereof at high-z is definitely needed.

Other evolutionary effects are still possible, in principle (e.g. Drell, Loredo & Wasserman, 1999; Hillebrandt 2000), however, as far as I am aware, only one that is physically meaningful, likely, and mimics accelerated expansion, has been identified so far.

This one potential evolutionary effect that certainly deserves more work is the effect of metallicity on the density at the point of carbon ignition. Generally, it is expected that a lower metallicity will result in a lower central density (e.g. Nomoto et al. 1997). This
is because a lower metallicity results in a lower abundance of the Urca-active element \(^{21}\)Ne, which in turn reduces the neutrino cooling and leads to an earlier ignition. A lower central density could (in principle at least) result in a more rapid light curve development (due to the lower WD binding energy), and a lower inferred maximum brightness.

It is important to note that in a recent work, Riess et al. (2000) have shown that it is highly unlikely that the dimming of distant SNe Ia is caused by dust opacity (Galactic-type dust was rejected at the 3.4\(\sigma\) confidence level, and “gray” dust with grain size \(> 0.1\) \(\mu\)m was rejected at the 2.3 to 2.6\(\sigma\) confidence level).

8. Tentative conclusions and observational tests

On the basis of the analysis and discussion in the present work, the following tentative conclusions can be drawn:

1. SNe Ia are almost certainly thermonuclear disruptions of mass accreting C–O white dwarfs.

2. It is very likely that the explosion occurs at the Chandrasekhar mass, as carbon is ignited at (or very near) the WD center. The flame propagates either as a deflagration, or, more likely perhaps, starting as a deflagration which transitions into a detonation. Off-center ignition of helium at sub-Chandrasekhar masses may still be responsible for a subset of the SNe Ia which are subluminous, but this is less clear.

3. The immediate progenitor systems are still not known with certainty. From the discussion in §5 (see in particular §5.1.3 and 5.2.3) however, I conclude that presently single degenerate scenarios look more promising, with hydrogen or helium rich material being transferred from a subgroup or giant companion (systems like Supersoft X-Ray Sources and Symbiotics). It is still possible, however, in view of the apparent diversity in the local sample, that more than one progenitor class contributes to the total SNe Ia rate. In particular, a scenario in which single degenerates contribute \(\sim 60\%\) of the events and double degenerates \(\sim 20\%\), appears to be consistent with the diversity of the \(z \sim 0\) sample and the lack thereof in the distant sample.

4. Definitive answers concerning the nature of the progenitors can be obtained from observations taken as early as possible in: \(x\)-rays, radio, and high resolution optical spectroscopy. The establishment of the presence or absence of hydrogen in SNe Ia should be regarded as an extremely high priority goal for supernova observers. If hydrogen will not be detected at interesting limits (corresponding to \(\dot{M}/v_{10} \sim 10^{-8}\) \(M_{\odot}\) yr\(^{-1}\)), this will point clearly towards the double-degenerate scenario.

5. Observations of SNe Ia at high redshifts can help to test particular ingredients of the models which are directly related to the nature of the progenitors. For example, most of the models aiming at improving the statistics of the single-degenerate scenarios rely on a strong wind from the accreting WD. These models thus predict an “inhibition” of SNe Ia in low-metallicity environments, and in particular a significant decrease in the rate of SNe Ia in spirals at \(z \sim 2\) (Kobayashi et al. 1998; Nomoto et al. 2000). Furthermore, if the inferred cosmic star formation rate is used (e.g. Pettini et al. 1998), then the SN Ia rate is expected to drop significantly at \(z \sim 1.6\). At present, the detection of a very likely SN Ia at redshift \(z = 1.32\) (SN 1997ff; Gilliland, Nugent & Phillips 1999) in the Hubble Deep Field, and two more at redshifts 1.20 and 1.23 (Perlmutter et al., private communication and Tonry et al., private communication) appear to be at least mildly inconsistent with this prediction, but more observations will be required to give a more definitive answer.

6. The potential “inhibition” of SNe Ia due to low metallicity should also manifest itself in an absence (or at least a significant decline in the rate) of SNe Ia in dwarf galaxies.
and in the outer regions of spirals. The statistics necessary to test this prediction are starting to accumulate.

(7) It is possible, in principle, that the local and high-z SNe Ia samples are dominated by different progenitor classes, thus mimicking accelerated expansion, however, this is neither very likely nor consistent with the observations of diversity. With more detections of SNe Ia at redshifts \( z \gtrsim 1 \) it will probably become possible to directly confirm the transition in the expansion of the universe from deceleration to acceleration. Such a transition would be difficult to mimic by systematic or evolutionary effects, and it would therefore confirm the accelerated expansion.

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