Cosmology with Supernovae

*The Road from Galactic Supernovae to the edge of the Universe*

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Abstract. This review gives an update of the cosmological use of SNe Ia and the progress made in testing their properties from the local universe to high–z. The cosmological road from high–z supernovae down to Galactic SNe Ia is followed in search of the answer to standing questions on their nature and their validity as cosmological indicators.

1. Introduction

The use of SNe Ia as calibrated candles has recently led to a fundamental discovery: that the rate of the cosmic expansion of the Universe is accelerating (Perlmutter et al. 1999; Riess et al. 1998). The presence of a energy component with negative pressure (still undistinguishable from the cosmological constant $\Lambda$) and the nature of this new component is a major challenge in Cosmology and in Fundamental Physics. Precise enough observations of SNe Ia extending to redshifts $z \sim 1.5 - 2.0$ should yield the equation of state of the new component (usually termed dark energy), $p_X = w_X \rho_X$, that is the relationship between pressure and energy density.

Both the new picture of the Universe that is now emerging and the next step in its investigation, that of determining the nature of dark energy, critically depend on the reliability of the calibration of SNe Ia luminosities, which up to now is purely empirical. While various efforts to build up large consistent samples of SNe Ia covering the $z$ range needed for cosmology are on their way, detailed analyses of the current high–z sample have shed new light into old questions.

2. The Use of Type Ia supernovae for cosmology

2.1. A brief historical account

Type Ia supernovae (SNe Ia) are explosions of carbon–oxygen white dwarfs (C+O WDs), very uniform in their physical properties. Their

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brightness and the possibility of calibrating their luminosity makes them very suitable distance indicators in cosmology.

In the first uses of SNe Ia to determine the cosmological parameters it was assumed that those objects were standard candles, implying that they all had similar luminosities. In 1977, Pskovskii realized that there was a correlation between the brightness at maximum and the rate of decline of the light curve: the brighter SNe Ia have a slower decline of their light curves whereas fainter ones would be faster decliners. A systematic follow–up of SNe Ia (Maza et al. 1994; Filippenko et al. 1992a,b; Leibundgut 1993; Phillips 1993; Hamuy et al. 1996a,b; Barbon et al. 1999) confirmed the brightness–decline relation. Phillips (1993), and Hamuy et al. (1996a,b) quantified it by studying supernovae at $z \sim 0.1$, a $z$ large enough that peculiar motions do not introduce dispersion in the magnitude–redshift diagram. The intrinsic variation of SNe Ia is written as a linear relationship of the sort:

$$M_B = -M_{Bt} + \alpha [\Delta m_{15}(B) - \beta] + 5 \log(H_0/65)$$

(1)

$\Delta m_{15}$, the parameter of the SNe Ia light curve family, is the number of magnitudes of decline in 15 days after maximum. The value of $\alpha$ as well as the dispersion of that relation have been evaluated in samples obtained from 1993 to the present (see Phillips et al. 1999). $M_{Bt}$ is the absolute magnitude in B for a template SN Ia of $\beta$ rate of decline.

Other groups have formulated the brightness–decline correlation in a different way. Riess, Press & Kirshner (1995a,b) use the full shape of the light curve with respect to a template. This is also the formulation used by the High–Z SN Team in their high–redshift supernova studies. The Supernova Cosmology Project collaboration, on the other hand, has introduced the stretch–factor, $s$ as a parameter to account for the brightness–decline relationship (Perlmutter et al. 1999, Goldhaber et al. 2001).

All different ways to parameterize the effect lead to equivalent results for the present value of the rate of expansion of the Universe $H_0$ and derive similar matter density $\Omega_M$ and cosmological constant density $\Omega_\Lambda$. Leibundgut (see this conference) shows that the corrections provided by different methods to the same supernovae are however different. By looking at the conversions between the MLCS, $\Delta m_{15}$ and stretch factor one sees that there are no linear relationships shifting one into the other and the approximate established conversions have some dispersion. While the overall results on the cosmological implications from supernovae are in agreement, it is important for the various methods to describe in a complete reproducible way the procedure in which the brightness–rate of decline relationship is measured.
Figure 1. The correlation maximum brightness–rate of decline of SNe Ia as described through the SNe Ia light curve shapes by Riess, Press & Kirshner (1995a).

The degree to which the brightness–rate of decline correlation reduces the scatter in the Hubble diagram is shown in Figure 2. On the other hand, the family of SNe Ia form a sequence of highly resembling spectra with subtle changes in some spectral features correlated with the light curves shapes (Nugent et al. 1998).

By using the magnitude–redshift relation $m(z)$ as a function of $\Omega_M$ and $\Omega_\Lambda$ with a sample of high–z SNe Ia of different $z$, Goobar & Perlmutter (1995) showed that it is possible to constrain, from observations, the region of allowed values in the $\Omega_M–\Omega_\Lambda$ plane. The relation goes as:

$$m(z) = M + 5 \log d_L(z, \Omega_M, \Omega_\Lambda) - 5 \log H_0 + K_c + 25 \quad (2)$$
where $M$ is the absolute magnitude of the supernova, $d_L$ the luminosity distance, and $K_c$ is the K-correction. The method is illustrated in Figure 3.

By 1998, such use gave important results in the two collaborations. Those results were presented in the $\Omega_M$–$\Omega_\Lambda$ plane and implied $\Omega_\Lambda > 0$ at a $3\sigma$ confidence level. For a flat universe ($\Omega_{Tot} = 1$), the results from the Supernova Cosmology Project implied $\Omega_M = 0.28^{+0.09}_{-0.08}$ (stat) $^{+0.05}_{-0.04}$ (syst), and the High–Z Supernova Team obtained for a flat universe $\Omega_M = 0.24 \pm 0.1$. The outcoming picture of our universe is that about 20–30% of its density content is in matter and 70–80% in cosmological constant. According to the allowed $\Omega_M$ and $\Omega_\Lambda$ values, the Universe will expand forever, accelerating its rate of expansion.
2.2. Questions answered in the last years

Two important questions were raised soon after the results from 1998 were known. The method finds Type Ia supernovae at high \( z \) being dimmer than what they should be for an Einstein–de Sitter universe or an open \( \Lambda = 0 \) Universe. Could just dust be responsible for that effect? (Aguirre 1999; Rowan–Robinson 2002).

A second important question relates to the universality of SNe Ia light curves. Do high-\( z \) and low–\( z \) SNe Ia show the same brightness–rate of decline relationship? A difference in the rise time to maximum between SNe Ia at low and high \( z \) was suggested in an early analysis by the High–Z SN Team (Riess et al. 2000). In general, one could ask whether evolution and environmental effects influence the observed SNe Ia light curves.

The most recent work has tried to clarify the above topics. Dust can be discriminated against a cosmological effect by going to a redshift beyond \( z \sim 1 \), where the predicted behavior of the curves differs significantly in each case, or/and by performing multicolor light curve analysis of the individual SNe Ia (Riess et al. 2000). SN 1997ff was a supernova in an epoch where the Universe was still decelerating and showed in the Hubble diagram that the effect measured by the two collaborations was not linked to an overall dust extinction that would cumulate with \( z \) (Riess et al. 2001).
In relation to the second question, that of the rise time to maximum of the supernova light curves, the study of a significant sample of SNe Ia at various $z$ by the Supernova Cosmology Project reveals that the rise times to maximum are similar in low–$z$ and high–$z$ SNe Ia (Aldering et al. 2000; Goldhaber et al. 2001). Statistical evaluation is so far consistent with no difference among the low–$z$ and high–$z$ samples.

Moreover, the possibility of existence of an extra parameter in the maximum brightness–rate of decline relation has been carefully examined. Among possible influences, metallicity was one of the obvious ones to consider. We know that it plays an important role in the Cepheid period luminosity–relationship which is widely used in distance determinations at more modest redshifts.

Work by Ivanov, Hamuy & Pinto (2000) has shed light on the issue. After examining supernovae in galaxies with a gradient of metallicity, they conclude that there is no evidence for metallicity dependence as an extra parameter in the light curve correlation of SNe Ia. Their result comes from an analysis of the SNe Ia light curves of a sample of 62 supernovae in the local Universe. The SNe Ia belong to different populations along a metallicity gradient. This check has been done as well at high–$z$ by Quimby et al. (2002) using 74 SNe Ia ($0.17 < z < 0.86$) from the SCP sample. No significant correlation between peak SNIa luminosity and metallicity is found. The tendency to have dimmer (and faster declining) SNe Ia in elliptical galaxies than in spirals, encompassing a narrower distribution in the brightness–rate of decline relationship, seems to be a population age effect. In former discussions of the evolutionary path that leads to SNe Ia, Ruiz–Lapuente, Canal & Burkert (1995, 1997) argued for a population–age effect in the change in the dispersion of sample properties between ellipticals and spirals: less massive and colder WD SN progenitors would be selected in older populations. Spirals would contain WDs with a wider spread in masses and degrees of cooling than ellipticals.

On the other hand, a study with the HST of the host galaxies of the SNe Ia sample of the Supernova Cosmology Project (Ellis & Sullivan 2000; Sullivan et al. 2002) suggests that, at high $z$, early–type galaxies do also show a narrower dispersion in SNe Ia properties than late–type galaxies, as they do at low $z$ (Branch, Baron & Romanishin 1996). This study deserves special attention as it clarifies different points on the link of SNe Ia properties with host galaxy type, the role of dust and the shift in properties in the family of SNe Ia. Sullivan et al (2002) examine the SCP (Perlmutter et al. 1999) sample according to its host galaxy type. The SNe Ia in spiral galaxies appear fainter and redder and show a larger scatter around the best–fitting cosmological model than the SNe Ia in E/S0 galaxies. The SNe Ia in dust–free galaxies like ellipticals show...
Figure 4. Figure from Sullivan et al. (2002). Upper panel: The stretch–corrected SNe Ia Hubble diagram plotted according to the type of the host galaxy. Lower panel: Residuals from the adopted cosmology ('fit–C' of Perlmutter et al. 1999 $\Omega_M = 0.28$ and $\Omega_\Lambda = 0.72$) for both high and low redshift SNe. The residuals of SNe Ia in E/SO galaxies are small.

The obvious explanation coming out of this work is that SNe Ia in late galaxy types suffer from increased extinction in the galaxy. The SNe magnitudes are corrected regularly from Galactic extinction, but the correction by dust residing in the host galaxy or along the line of sight is not included in the standard fit, as it would require to have extensive color information that might not be available for high–z SNe Ia. An interesting discussion on the limits of dust extinction as probed by this sample can be found in that paper, and it helps to quantify the role of dust in making supernovae fainter.
Moreover, Sullivan et al. (2002) and Farrah et al. (2002) tested as well the sample of high-z SNe Ia along projected radius in their host galaxies. Farrah et al. (2002) found no evidence that the SNe Ia at \( z = 0.6 \) are preferentially found in outer regions (\( > 10 \) kpc) of host galaxies where extinction would be low. This suggests that the range of host galaxy extinctions of SNe Ia at \( z \sim 0.6 \) is comparable to that of local SNe Ia. No significant trends were found in stretch and other properties along projected radius between the low z and high z samples as well (Sullivan et al. 2002).

Another second interesting aspect examined in this work is the possibility of a shift in the population distribution between SNe found at low and high redshift: at high redshift we see in the Perlmutter et al. (1999) sample no trend in stretch with galaxy type, whereas at low redshift SNe with larger stretches (slow decliners) are found in later–type galaxies and are missing from \( E/S0 \) galaxies (though this is a tentative result given the size of the high–z sample).

The reader will note that here we are talking about the spread of the SNe Ia samples in galaxies of different types: on how many fast
SNe Ia versus intermediate or slow decliners are found in the various morphological types. Spirals at low or moderate redshifts should encompass all ranges of variation in the SNe Ia properties since they contain populations with a wide spread in age. The cosmological collaborations keep finding that in those samples the one–parameter correlation does give a good description of the variation of the SNe Ia light curves (Riess et al. 2000; Goldhaber et al. 2001).

The fact that in old populations SNe Ia are systematically dimmer than in young populations could be interpreted in terms of what affects the progenitors of the SNeIa: the WDs. A population age effect that we favor (Ruiz–Lapuente et al. 1995; Ruiz–Lapuente et al. 1997), as we have mentioned above, is linked to the time the WD has cooled before reaching the point of explosion. This affects the amount of neutronized material synthesized at the center of the exploded WD and the overall nucleosynthesis. Another possible effect is related to the composition of the accreted material added to the initial WD till the explosion occurs. If the WD gains mass by accreting H from a non-WD companion and burning it to He and C+O, and the initial mass of the WD is smaller (although not by a large factor) in an old population, the star needs to add up more material before reaching the explosion in old than in young systems. This creates differences in the composition of the outer layers of systems belonging to different populations and that could be reflected in the final brightness–rate of decline relation (by an opacity effect). We favor, however the first (cooling) effect, since the typical age of the binary system when it reaches explosion is quite long, in the most likely SNIa picture. For the WDs exploding as SNe Ia, typical ages $\sim 5 \times 10^9$ yr and a small mass variation between $z = 0$ and $z = 0.8$ are found.

In the 3–D hydrodynamic simulations of WD explosions by Hillebrandt et al. (2000), the family of SNe Ia seems to arise from different conditions at the start of the thermonuclear burning of the C+O WD, in particular, the number/location of spots where the ignition starts and the density at which the ignition takes place. Different results for the nucleosynthesis are obtained: a more complicated topology of the initial flame seems to lead to higher Ni–production and, consequently, more powerful and brighter explosions (Reinecke, Hillebrandt & Niemeyer 2002). Light curves for this consistent set of models reproduce well the observations (see Blinnikov at this conference; Blinnikov & Sorokina 2000). As the initial conditions in the convective core of the WD in the pre–explosion stage are very critical for the development of the burning (Garcia–Senz & Woosley 1995), it seems natural to think that those factors determining the outcome are linked to the cooling undergone by the WD prior to explosion.
3. Modeling of Type Ia SN at various $z$

The discovery of the accelerating expansion of the Universe was mostly based on observations of SNe Ia at $z \sim 0.5$. The currently preferred values for the matter density $\Omega_M \sim 1/3$ and the dark energy density $\Omega_\Lambda \sim 2/3$ imply that the expansion began to accelerate at $0.5 < z < 1.0$, that is between 4.3 Gyr and 6.7 Gyr ago. There was a gap centered around $z \sim 0.2$ between the local sample and the high–redshift one, which we aimed to fill. To help in those cosmological studies we have carried out observations and done the modeling of SNe Ia in a restricted $z$ interval chosen to be $z \sim 0.15 - 0.35$. We are placing our emphasis on investigating systematic effects and comparing theoretical and observed light curves by modeling the explosions of WDs (hydrodynamics, nucleosynthesis) and the corresponding light curves.

Table I. SNeIa targeted in the International Time Programme

| SN Targets | $z$  | SN                              | Subprogramme         |
|------------|------|---------------------------------|----------------------|
| Nearby     | $< 0.016$ | SN 2002bo, SN 2002dj, SN 2002er | Intensive follow up  |
| Medium-z   | 0.1-0.3 | Completion of a sample of 20 SNe Ia | Cosmology           |

As it had been shown by previous campaigns, within that redshift interval observations with 4.2m–2.5m telescopes can still be complete enough to explore possible deviations of the peak luminosity–light curve shape relationship from the local one, including the faintest SNe Ia, check for correlations of SNe Ia properties with galaxy type and with location inside a given galaxy, and measure intergalactic extinction. In addition, improved accuracy on the evolution of the SNe Ia rate along $z$ should result. Finally, the interval being well within the acceleration era, the SNe Ia observations can contribute valuable information on $w_X(z)$ itself.

The searches of SNe Ia at redshifts centered around $z \sim 0.2$ used the Wide Field Camera (WFC) on the 2.5m INT. That telescope was used as well for the follow up. Spectroscopy was obtained at the 4.2m WHT allowing a classification of the supernovae. The first campaign took place in March–April 1999 and led to the detection of 19 SNe.

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1 Members of the European Supernova Cosmology Consortium involved in the first campaigns are P. Astier, C. Ballard, G. Blanc, S. Blinnikov, R. S. Ellis, S. Fabbro, G. Garavini, A. Goobar, D. Hardin, I. Hook, M. Irwin, R. G. McMahon, J. Méndez, M. Mouchet, A. Mourao, S. Nobili, J. Rich, P. Ruiz–Lapuente, K Schahmaneche, E. Sorokina, R. Taillat, N. Walton.
Figure 6. SNe Ia at intermediate $z$ found in campaigns by the ESCC. The lower panel shows the spectra of four SNe Ia discovered during the 1999 campaigns (Hardin et al. 1999; Pain et al. 2002). The upper panel shows the good sampling of the light curves obtained in the spring 2002 campaign which was conducted within the International Time Programme $\Omega$ and $\Lambda$ through SNe Ia and the Physics of Supernova Explosions, carried out at the telescopes of the ENO at La Palma (Ruiz–Lapuente et al. 2002a).
Ia candidates from which 2 were identified as SNe Ia (Hardin et al. 2000). This first INT run searched 12 sq degrees in R and B with magnitude limit 23 in B and 22 in R. Rates of SNe Ia at $z = 0.3$, as determined by Pain et al. (1996) are 20 SNe Ia degree$^{-1}$ night$^{-1}$ 0.5 mag$^{-1}$. For 1 night and integrating for 6 half magnitudes this implies rates of 0.33 SNe Ia sq deg$^{-1}$ night$^{-1}$ between mag 18 and 21. The discoveries made seemed consistent with early findings (Pain et al. 1996). The September–October INT run obtained 15 candidates by searching 30 sq degree in $g'$ up to a magnitude limit $g' \sim 22.5$. The mean $z$ of the 8 confirmed SNe Ia is $\langle z \rangle = 0.3$ (Hardin et al. 2000). During March–April 2000 we developed our campaign in combination with EROS, aimed to the discovery of SNe Ia at low $z$. 10 SNe Ia were identified at a $\langle z \rangle = 0.05$. The most recent campaigns (Ruiz–Lapuente et al. 2002a) have gathered a sample of 10 SNe Ia at $\langle z \rangle = 0.2$. 

Figure 7. SN 2002bo in NGC in NGC 3190 (Benetti et al. 2002). Intensive spectroscopic follow-up within the programme *The Physics of Type Ia Supernova Explosions* and the ITP on $\Omega$ and $\Lambda$ from SNe Ia and the Physics of Supernova Explosions.
Figure 8. Type Ia SNe made out of stars at various $z$ can be identified as responsible for the extragalactic $\gamma$–ray background in the MeV range (Ruiz–Lapuente, Cassé & Vangioni–Flam 2000). The background light produced by SN basically arises from SN up to $z \sim 1$. SNe Ia rates compatible with the results from optical supernova searches give a background emission in the MeV range that can indeed explain the extragalactic emission measured by COMPTEL and SMM.

In parallel with the empirical exploration of SNeIa properties along $z$, we have undertaken the detailed photometric and spectroscopic study of a sample of nearby SNe Ia discovered before they reached maximum light. Within this frame, intensive studies of three SNeIa in the local Universe were done$^2$. Figure 8 shows the intensive spectroscopic follow up done for SN 2002bo (Benetti et al. 2002).

Questions related to the physical spread of the SNe Ia family, will ultimately point towards the way the white dwarf accretes mass and reaches the state immediately preceding the explosion. The nature of the binary system in which SNe Ia take place is still unknown. A program to look for the companion star in the two historical SNe Ia in the Galaxy have yielded some constraining results (Ruiz–Lapuente et al. 2002b).

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$^2$ Work done in collaboration with the Asiago and ESO observatories within the European Research and Training Network on Physics of SNe Ia. [http://www.mpa-garching.mpg.de/rtn](http://www.mpa-garching.mpg.de/rtn)
Figure 9. Calculated synthetic spectra compared with the observed spectra of the SN companion candidates near the center of SN 1572. These are the closest red giants and supergiants to the center of the explosion. Their surface gravity goes from log g=2 for Tycho A to log g=0 for C and E. The effective temperatures for those stars are similar. They are in the range 4200–4500 K. Model atmospheres with solar chemical abundances give a good account of the spectra. The overall spectral comparison allows us to exclude overabundances of the Fe–peak elements. Moreover, the stars show no enhancement of iron–peak elements versus intermediate–mass elements in the spectra. Synthetic spectra are shown with bold continuous lines. Those comparisons rule out some systems as progenitors of the Galactic SNeIa (Ruiz–Lapuente et al. 2002b).
4. Stars giving Type Ia SNe

4.1. SNeIa efficiencies and progenitors

The high–z supernova searches not only allow to trace the expansion history of the Universe and provide a new picture of its matter–energy contents, but they also throw new light on a number of important astrophysical questions.

The SNe Ia production efficiency will first give us clues as to the nature of the so far elusive SNe Ia binary progenitor systems.

We know that the exploding star giving rise to a Type Ia SN is a carbon–oxygen white dwarf (C+O WD) and that there is no compact object left in the explosion. Stellar evolution arguments tell us as well that those explosions take place in binary systems. Up to recently, there was no clear evidence favoring any particular kind of binary system as responsible for the Type Ia phenomenon. Two candidate systems were proposed. One possibility is that SNe Ia arise from a binary made of a pair of C+O WDs that merge as their orbit shrinks due to the emission of gravitational wave radiation. This system is referred to double degenerate. The other candidate system is a WD which accretes material from a Roche–lobe overfilling non-WD companion (WD plus Roche–lobe filling subgiant, giant or main sequence star). The system contains only a WD and therefore is a single–degenerate system (see Branch et al. 1995; Ruiz–Lapuente et al. 1997; Livio 2000 and references therein).

If we evaluate the number of SNeIa exploding per unit comoving volume in redshift space $\mathcal{R}_{Ia}(z)$ relative to the mass going into forming stars in the Universe $\dot{\rho}_\star(z)$, we have a quantity that gives the efficiency of stars in producing SNe Ia along $z$ space. We can express this efficiency as $E_{SNeIa}(z)$:

$$E_{SNeIa}(z) = \mathcal{R}_{Ia}(z) \frac{yr}{Mpc^3} / \dot{\rho}_\star(z) \frac{M_\odot yr^{-1} Mpc^{-3}}$$

The quantity $E_{SNeIa}(z)$ above is just the number of SNe Ia per unit mass spent in forming stars at a given $z$, and it is independent from the cosmological model assumed. The absolute values of $E_{SNeIa}(z)$ reflect the abundance of progenitor systems (and thus the range of initial conditions leading to SNe Ia). It also reflects the evolutionary time scale (from birth to explosion) of the progenitor systems, together with other possible evolutionary effects. The single degenerate systems (made of a WD accreting from a non–WD companion) have evolutionary time scales of the order of a few Gyr whereas the double degenerate systems
Table II. Observations of SN 1572

| Run | Rd (′) | m_R | Telescope          | R     | Spec Range (Å) | stellar types       |
|-----|--------|------|--------------------|-------|----------------|---------------------|
| (1) | 0.7    | 14   | WHT (UES)          | 50,000| 4000–7100      | red giant           |
| (2) | 0.7    | 23   | WHT (ISIS)         | 15,000| 4600–7500      | red giants to WD    |
| (3) | 0.7    | 23   | Keck (ESI)         | 7000  | 4000–10000     | as above            |

Table III. Observations of SN 1006

| Run | Rd (′) | m_R | Telescope          | R     | Spec range (Å) | stellar types       |
|-----|--------|------|--------------------|-------|----------------|---------------------|
| (1) | 5      | 13   | NTT (EMMI)         | 10,000| 3950–7660      | red giants          |
| (2) | 5      | 15   | VLT (UVES)         | 50,000| 3500–9000      | all types           |

1 Radius of the search
2 Limiting magnitude
3 Telescopes(Instrumentation)

(coming from the merging of two WDs) have time scales of the order of a few hundred million years only.

Despite the uncertainties inevitably involved, the high–z searches have nevertheless brought some crucial information. The measurements of the cosmic evolution of the SNe Ia rate now extend up to \( z \sim 0.55 \) (Pain et al. 1996; 2002). The mean value of \( \mathcal{E}_{SNeIa}(z) \) over the redshift interval \( 0 < z < 0.55 \) corresponds to 1 SNeIa per \( 709^{+200}_{-157} \) \( M_\odot \) spent in forming stars. The low–redshift efficiencies (\( z \sim 0 \)) correspond to 1 SNeIa per \( \sim 900 \) \( M_\odot \) going into star formation, reaching 1 SNIa per \( \sim 700 \) \( M_\odot \) at \( z \sim 0.55 \). The efficiency of binaries in ending as SNeIa is 6% of the stars between \( 3 \sim 9 \) \( M_\odot \). Therefore, the channels that give rise to such high efficiency in giving SNeIa have to be wide.

A more decisive test comes from the fact that in SNeIa from single degenerate systems, we can expect detecting motion of the non–WD companion imparted when the systems disrupts, and that could be the key to the final identification of the SNe Ia progenitor systems (Ruiz–Lapuente 1997; Marietta, Burrows & Fryxell 2000; Canal, Mendez & Ruiz–Lapuente 2001). Since 1997 (Ruiz–Lapuente 1997) searches for
the moving companions of SN 1572 and SN 1006 have been performed. High resolution spectra of the stars within the radius of the historical remnants have been taken (see Table II and III) and their radial velocities have been measured. The spectra of these stars have been modeled to test for contamination by the supernova explosion. The lack of significant radial velocities and contamination from the SN explosion in these stars (see results for SN 1572 in Ruiz–Lapuente et al. 2002b) puts severe constraints on the progenitors. Ultimately, it comes out that going back to the Galaxy is needed to tie up the loose ends.

5. Prospects for dark energy measurements along $z$

If the SNe Ia results are correct, as they seem to be, our Universe is accelerated by a component which has a negative pressure. It has been discussed that it is possible to test gravitation theories by going to a higher level of analysis using Type Ia SNe (Weller & Albrecht 2001). Possibilities include testing SUGRA potentials, as discussed in many recent papers. The solution corresponding to the cosmological constant could be discriminated against quintessence or other scalar field models (Huterer & Turner 1999; Steinhard et al. 1998). Several experiments are under way to shed light on the nature of the dominant component of our Universe by observing a large number of SNe Ia up to $z = 1.7$. Strategies for a better discrimination of the dark energy are discussed by Huterer & Turner (2000).

The observational determination of $w$ and its variation with $z$ has already started: while the Supernova Cosmology Project is enlarging the sample of high–$z$ SNe Ia, the SNfactory\textsuperscript{3} will provide an anchoring in the low–$z$ domain with hundreds of SNe Ia below $z = 0.2$. ESSENCE\textsuperscript{4} plans as well to follow $\sim 200$ SNe Ia in the $z$ interval $0.15$–$0.75$ over a five year period. About a thousand SNe Ia discoveries are expected to come from the CFHTLS\textsuperscript{5} during the next 5 years, with preliminary results on the equation of state, while in the very high–$z$ range the GOODS $HST$ Treasury Program\textsuperscript{6} can bring supernovae to test the epoch of the deceleration of the Universe ($z > 1$). To add to this the intermediate $z$ searches and the very nearby ones\textsuperscript{7} should greatly enhance the knowledge of SNe Ia and reinforce their cosmological use.

\textsuperscript{3} http://SNFactory.lbl.gov
\textsuperscript{4} http://www.ctio.noao.edu/essence
\textsuperscript{5} http://www.cfht.hawaii.edu/Science/CFHTLS
\textsuperscript{6} http://www.stsci.edu/ftp/science/goods
\textsuperscript{7} http://www.mpa-garching.mpg.de/ rtn
Ultimately, to unveil the nature of dark energy, ground–based programmes are limited in accuracy and scope. It seems unavoidable to go to a fully devoted mission from space, such as SNAP\(^8\) to achieve an improved level of accuracy in the cosmological measurements, and to be able to discriminate among possible candidates to dark energy.

From all the above one sees that the various steps in the road to test the cosmological implications of SNe Ia will be taken. Thus, we expect the next years to bring definitely an understanding of what lies behind the observed acceleration of the expansion of the Universe.

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