Supernovae and Cosmology

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Abstract

The extreme luminosity and their fairly unique temporal behaviour have made supernovae a superb tool to measure distances in the universe. As complex astrophysical events they provide interesting insights into explosion physics, explosive nucleosynthesis, hydrodynamics of the explosion and radiation transport. They are an end product of stellar evolution and provide clues to the stellar composition. Since they can be observed at large distances they have become critical probes to further explore astrophysical effects, like dust properties in external galaxies and the star formation history of galaxies. Some of the astrophysics interferes with the cosmological applications of supernovae. The local velocity field, distorted by the gravitational attraction of the local large scale structure, and the reddening law appear at the moment the major limitations in the accuracy with which cosmological parameters can be determined. These absorption effects can introduce a secondary bias into the observations of the distant supernovae, which needs to be carefully evaluated. Supernovae have been used for the measurement of the Hubble constant, i.e. the current expansion rate of the universe, and the accelerated cosmic expansion directly inferred from the apparent faintness of the distant supernovae.

1 Introduction

The energetic display of a supernova marks the transition from a bound star to the recycling of material into the gas pool of a galaxy or beyond. The progenitor star at explosion could still have an active nuclear furnace operating or could be a degenerate end product of stellar evolution. The corresponding results also take different forms: a compact "stellar" remnant, a neutron star or a black hole as the result of a collapse of the stellar core, or no compact remnant, when the star is incinerated by a nuclear explosion. In all cases, the expelled material will interact with its environment and produce a supernova remnant. One of the main topic of interest is how the different physical processes lead to the observed displays. As further exposed in the following, some of the uncertainties in our understanding of the supernova physics limits their use in cosmological applications.

Supernovae shaped today's universe in many different ways. They are the main mechanism to create heavy elements, especially the ones only created in explosive nucleosynthesis. They are also responsible for the return of these newly created elements into the baryonic cycle of dust, gas and stars. The energy input into the interstellar material can be so significant that star formation can be triggered or suppressed. For smaller galaxies, supernovae most likely shape their appearances. Cosmic ray acceleration is most probably done in the shock of supernova remnants and the collapse of massive stellar cores are the main source of neutrinos beyond the Big Bang.

Supernovae appear in very different displays. In fact, a clear definition of a supernova does not exist. There is a classification scheme, which dates back to Walter Baade, Fritz Zwicky and Robert Minkowski (Baade & Zwicky 1934, Minkowski 1941, 1964). For a modern version with detailed definitions see Filippenko (1997). A supernova in the following will be the event when a star ejects most of its material in a violent explosion and ceases to exist as a stellar entity. Note that this is a physical description, while the observations we obtain are often not able to definitely ascertain that the above condition is fulfilled. Nevertheless, a supernova by definition cannot be recurrent. It marks the end of the existence of a star as an individual object. One should note that this definition includes $\gamma-$ray bursts together with the more traditional supernova classes.

Due to their luminosity supernovae have been a favourite for cosmological applications. They are also markers of star formation and could be amongst the earliest objects we may be able to observe in the early universe.

This article first presents a brief history of supernovae. It will then comment on the current classification scheme and its use to understand the explosion physics and the radiation hydrodynamics, which takes place in these explosions. Supernovae as cosmological distance indicators will be examined first before we will move on to a discussion of the Hubble constant and the expansion history of the universe as derived from supernovae. The latter is currently concentrated on Type Ia supernovae (SNe Ia hereafter), which have been the most successful in measuring distances half way across the universe.

The literature on supernovae and their cosmological applications has literally exploded in the past decade. There are the classic papers, which will be mentioned in this review, but also many associated interpretations. Overviews have been presented in recent monographs on supernovae and gamma-ray bursts (e.g. Niemeyer & Truran 2000, Hillebrandt & Leibundgut 2003, Weiler 2003, Höflich et al. 2004, Marcaide & Weiler 2005, Turatto et al. 2005). Supernova physics is reviewed in Filippenko (1997), Hillebrandt & Niemeyer (2000), Leibundgut (2000) and Woosley & Bloom (2007). Several reviews of the supernova cosmology have been published as well (Branch 1998, Riess 2000, Leibundgut 2001, Perlmutter & Schmidt 2003).

1.1 Some early history

The appearance of new stars, "stellae novae" from their Latin designation, has always intrigued astronomers as documented in the ancient Chinese and Korean records (see Clark & Stephenson (1977) and Murdin & Murdin (1978) for reviews of the historic supernovae in the Milky Way observed over the last two millennia).

The first to suggest that there are two classes of novae was Lundmark (1925), who proposed an 'upper class' about 10 magnitudes brighter than the 'lower class' of novae. The latter would correspond to the well known Galactic novae. He based his proposal mostly on the observation of the (super)nova 'S Andromeda' observed in 1885 (designated SN 1885A in modern nomenclature), which appeared that much brighter than a sample of about two dozen regular novae in the Andromeda galaxy. Lundmark later seemingly was the first to suggest the name 'super-nova' (Lundmark 1932).

It was Walter Baade who made the connection between the historical supernovae and the observed emission nebulae at their positions, thus identifying the remnants of the explosions. The most prominent object is of course the Crab Nebular (Messier 1), the leftover from the supernova in 1054 (Baade 1942, Mayall & Oort 1942). With extensive observations of bright supernovae Minkowski (1941) introduced two subclasses. Zwicky (1965) refined the classification scheme for supernovae further. However, for several decades only two main classes were maintained until in the early 1980s it became clear that at least one further subclass needed to be added. The classification scheme has now expanded again with the introduction of several subclasses to further distinguish between different observed displays. Some proposals mix spectroscopic definitions with the light curve appearance, while others even introduced theoretical arguments into the classification. The reason for a classification scheme should remain simple and it should not be mixed with theoretical ideas. While different behaviour clearly indicates different physics, the classification as used in the past was primarily to quickly plan observing strategies and give an indication what type of event was observed. This still is often the case for the projects, which make use of SNe Ia for cosmology, as the spectroscopy time needs to be used as efficiently as possible.

2 Supernova classification

The modern classification of supernovae is based on the spectroscopy at maximum light (e.g. Filippenko 1997, Turatto et al. 2003 - see also Fig. 1). The distinction is done through the presence (or absence) of hydrogen lines in the optical spectra near maximum brightness leading to the classes of Type II supernovae (or Type I supernovae). The hydrogen-deficient supernovae are further subdivided into groups which display prominent absorption near 6150Å attributed to a transition in singly ionised silicon (Si II in astronomical notation) for the Type Ia supernovae and others which show sodium and oxygen absorption lines, designated Type Ib/c supernovae (Fig. 1). The separation of these two subclasses happened during the early 1980s, when it became clear that there was a subset of Type I supernovae that showed very red colours, a spectral evolution, which appeared accelerated, and showed lines of intermediate elements at late phases (Wheeler & Levreault 1985, Uomoto & Kirshner 1985, Panagia et al. 1986, Filippenko & Sargent 1986). The presence/absence of helium lines is used as a separation into the Type Ib/Type Ic supernovae, respectively. The exact physical interpretation of this separation remains relatively weak. An evolutionary sequence for the separation of these core-collapse supernovae has been proposed, in which the appearance is determined by the amount of hydrogen envelope remaining on the star at the time of explosion. Regular stars with a thick hydrogen layer would explode as SNe II, while the ones which lost this hydrogen layer, e.g. due to a strong stellar wind or interaction with a binary companion, would become SNe Ib. Should the helium layer be eroded as well, then a SN Ic is observed. Moreover, there is one 'cross-over' class of Type IIb supernovae, with the prominent example of SN 1993J. These events typically start out as hydrogen-displaying supernovae (hence SN II) before the hydrogen lines disappear and the objects start to resemble Type Ib/c supernovae. They represent the major link showing that the SNe Ib/c are core-collapse supernovae. Figure 1 also lists some prominent examples for each SN class.

A physical picture for this classification scheme has emerged. The Type Ia supernovae are coming from thermonuclear explosions of stars, which have shed hydrogen and helium during their progenitor evolution. Hence no traces of these elements are observed in these explosions. All other supernovae most likely come from the core collapse in massive stars or in some cases more exotic phenomena, like pair instability (e.g. Heger et al. 2003). The signature for these events are their oxygen and calcium rich spectra at late phases.

It is notable that gravity is the ultimate reason for both types of explosions. In the cores of massive stars the hydrostatic equilibrium is maintained by burning to higher and higher elements at increasing temperatures. By the time the core has burnt its fuel to iron no further exothermic reactions are possible and the stellar core collapses under the weight of the outer layers of the star. The collapse is only stopped when the material reaches nuclear densities where electrons and protons merge and create neutrons. At this stage the proto-neutron star provides a hard surface. The neutrinos created in this process emerge mostly without interacting, but even a tiny amount of energy deposited by the neutrinos in the envelope can turn the implosion into an explosion. The exact mechanism has not been fully explored, but at least small stars ($8 - 10\ \mathrm{M}_\odot$) can now be made to explode moderately by the modellers (Kitaura et al. 2006).

Hypernovae have been added to the list of supernovae and they represent the high energy end (at least in their kinematics) with the large expansion velocities observed in these objects. The connection of gamma–ray burst with supernovae has now been generally accepted with the observations of SN 2003dh/GRB030329 (Stanek et al. 2003, Matheson et al. 2003, Hjorth et al. 2003). It should be noted that already SN 1998bw/GRB980425 showed all the signatures of a supernova (Galama et al. 1998, Patat et al. 2001). Hypernovae are characterised by the absence of hydrogen and helium and very high expansion velocities observed in their spectra (Mazzali et al. 2002, 2003, Woosley & Bloom 2007). In some cases no gamma-ray burst is observed, like for SN 2002ap. The amount of nickel synthesised in these explosions is substantial (up to about 0.5 $M_\odot$; Sollerman et al. 2002). The kinetic energies inferred from the line widths are also substantially larger than the ones of regular SNe II. In many aspects they appear to be similar to the SNe Ib/c with high kinetic energy.

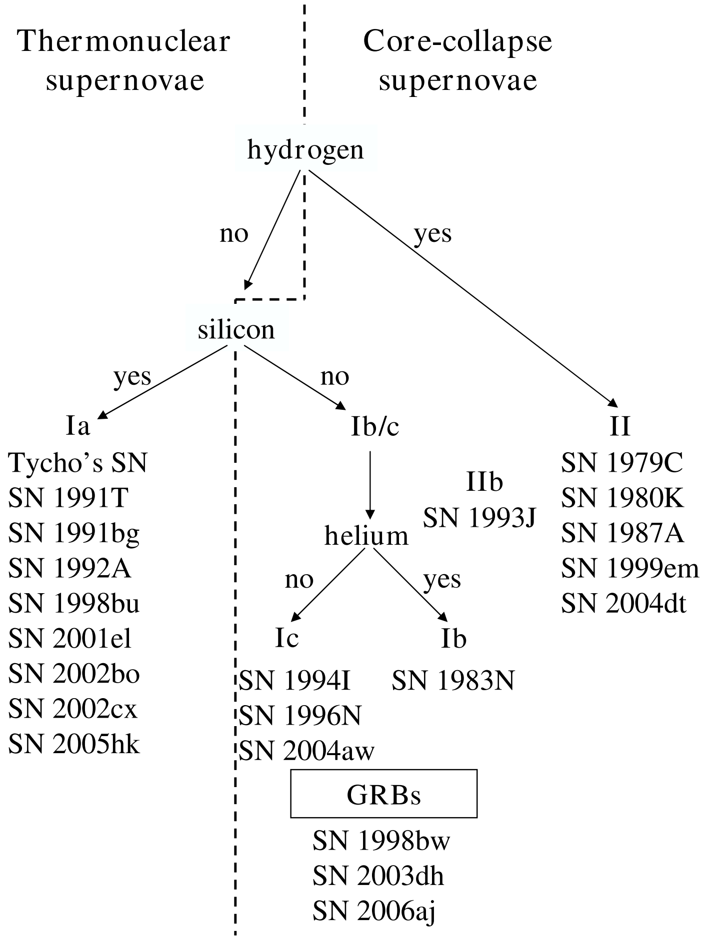

Figure 1: Classification scheme for supernovae. The presence or absence of specific absorption features in the maximum-light spectrum is used to separate the supernovae into different classes. The SNe Ia are the only ones which are thought to come from the thermonuclear explosion of a white dwarf. All others are powered by the core collapse in a massive star. Prominent examples of the various classes are indicated.

In the case of the thermonuclear supernovae the electron-degenerate white dwarf has to cope with an increasing amount of material piled onto it by a companion star, and hence increases the pressure and temperature in the core. Again, it is the gravitational force which sets off the explosion, in this case the explosive carbon and oxygen burning, which disrupts the star. A comparison of the binding energy of a neutron star or the binding energy of a solar mass of iron give a clear indication of how much energy is released in these explosions.

Some objects cannot be clearly classified into one or the other class. Prime examples are SN 2002ic and SN 2006gy, which both have been interpreted as possibly a thermonuclear explosion or a core-collapse. While SN 2002ic has all the traits of a thermonuclear supernova it also displayed a strong hydrogen Balmer Hα emission line (Hamuy et al. 2003). This latter fact has led to an investigation whether SN 2002ic could not be a core-collapse supernova (Benetti et al. 2006). SN 2006gy is a very energetic supernova clearly showing strong Hα emission, but a very slow light curve. One interpretation argues for possibly the first observation of a pair-instability supernova (Smith et al. 2007), while another study finds that this could be a thermonuclear supernova within a dense circumstellar shell (Ofek et al. 2007). Such cases show the difficulty to uniquely map the classification scheme into the physical interpretation of the events.

3 Core-collapse supernovae

The richness in appearance of the core-collapse supernovae is due to their varied progenitor histories. Spectra observed near maximum light show Hα in these events, but with a wide variety (e.g. Filippenko 1997, Leibundgut 2005). The typical light curves of SNe II display a long plateau of about 100 days after the maximum. The most prominent and best observed case after SN 1987A is SN 1999em (Hamuy 2001, Leonard et al. 2001, Elmhamdi et al. 2003). SN 1987A taught us a lot about core collapse supernovae (for reviews see Arnett et al. 1989, McCray 1993, Leibundgut & Suntzeff 2003, McCray 2005). While SN 1987A displayed a strong P Cygni line of Hα, it is almost not visible in SN 1993J. The latter lost this line in its evolution completely and only after about one year did Hα reemerge in the nebular spectrum (Filippenko et al. 1994). The case of SN 1988Z is different again. In this case, the hydrogen is excited in circumstellar material shocked by the supernova ejecta. The emission is dominated by the shock energy and not recombination or radioactive decay as in most other supernovae.

This special case of supernovae interacting early on with their dense circumstellar environment is discussed in Chevalier & Fransson (2003) and Leibundgut (1994). They typically have very slow light curves and spectra that show emission lines but very little absorption. The best studied cases so far are SN 1986J (Leibundgut et al. 1991), SN 1988Z (Turatto et al. 1993), SN 1995N (Fransson et al. 2002) and SN 1998S (Fassia et al. 2000). All of these objects are strong radio emitters (reviews on the radio emission are available from Weiler & Sramek 1988 and Weiler et al. 2002). The radio observations in particular allow to trace the mass-loss history of the progenitor star with interesting conclusions on their final evolution. These objects often can be observed for many years. The poster child for a shock interacting with circumstellar material is of course SN 1987A, which recently transitioned from a teenager into a maturing supernova remnant (McCray 1993, 2005, Fransson et al. 2007).

Extreme examples of this class of supernovae demonstrate their diversity. Examples are the GRBs (reviews in Weiler 2003 and Woosley & Bloom 2007), the recent, very energetic SN 2006gy (Ofek et al. 2007, Smith et al. 2007), the very faint objects like SN 1987A and the Type Ib/c events, which are presumably stripped of their envelopes either by massive stellar winds or mass loss to a companion star. All these different appearances are a signature of the variety the evolution of massive stars leading to different configurations at the time of explosion.

Several proposals have been made how core-collapse supernovae could be used as distance indicators. They will be discussed in §5.1.1.

4 Type Ia supernovae

Although thermonuclear supernovae have simpler underlying physics than the core-collapse supernovae, there still remain formidable hurdles to fully understand them (Hillebrandt & Niemeyer 2000). The observational material that has been assembled in the last decade is considerable and many nearby supernovae are now observed with exquisite detail. The last few years have seen dramatic progress in recognising peculiar events and also determining specific characteristics. The situation a few years ago is described in Leibundgut (2000). Since then the peculiar SN 2000cx (Li et al. 2001, Candia et al. 2003) and SN 2002cx (Li et al. 2003) have been observed. A truly particular case has been discovered in SN 2002ic (Hamuy et al. 2003), which displayed a strong, broad-lined Hα emission after about 90 days past the maximum. This supernova displayed the signatures of a bright SN Ia with what looked like residual Hα emission from the host galaxy. The spectral sequence later showed that the hydrogen emission is intrinsic to the supernova and indicates that this explosion occurred inside a dense hydrogen cocoon. Such events throw a dark shadow over the light curve *vs.* luminosity relations that have been used in the past to normalise the peak luminosity (Phillips 1993, Hamuy et al. 1995, Riess et al. 1996a, 1998, Perlmutter et al. 1997, Phillips et al. 1999, Goldhaber et al. 2001, Wang et al. 2003a, 2006, Guy et al. 2005, 2007, Prieto et al. 2006, Jha et al. 2007) necessary to derive accurate cosmological distances. The differences for individual objects highlight the fact that not all SNe Ia are identical and provide us with a tool to further investigate the true nature of these explosions.

The main observables of supernovae remain the optical and near-infrared light curves and spectral evolution (e.g. Leibundgut 2000). Spectro-polarimetry in the optical has matured significantly over the past decade and several SNe Ia have significantly polarised light and also remarkable evolutions (Kasen et al. 2003, Wang et al. 2003b, Leonard et al. 2005, Wang et al. 2007). Very few observations at wavelengths outside the optical and near-infrared window have been obtained. Only two events have so far been observed in the thermal infrared, SN 2003hv and SN 2005df (Gerardy et al. 2007). The detection of emission lines of nickel and cobalt over 100 days after explosion indicates a surprisingly large amount of stable nickel in the ejecta. Also, prominent lines of argon ([Ar II] $\lambda 6.985\mu$m) with a double-horned profile are detected. The observations hint at a stratified composition of the ejecta, which cannot be explained well with the current models. So far not a single SN Ia has been detected at radio wavelengths (Panagia et al. 2006) and only one X-ray detection of a peculiar event has been reported (SN 2005ke, Immler et al. 2006).

Many optical and near-infrared light curves have become available. Large collections of light curves are available from the Calán/Tololo and the Carnegie projects (`http://csp1.lco.cl/~cspuser1/PUB/CSP.html`: Hamuy et al. 1995, Phillips et al. 1999, 2006, 2007, Krisciunas et al. 2001, 2003, 2004a,b,c, 2006, 2007), the *CfA* group (`http://www.cfa.harvard.edu/supernova/`: Riess et al. 1996a, 1999a, Jha et al. 2006a), the Berkeley group (Filippenko et al. 1992a,b, Li et al. 2001, 2003) and the more recent European Supernova Consortium (`http://www.mpa-garching.mpg.de/~rtn/`: Pignata et al. 2004, Kotak et al. 2005, Elias-Rosa et al. 2006, Pastorello et al. 2007a,b, Stanishev et al. 2007, Garavini et al. 2007a).

Most of the very early photometric observations have been provided by these projects (SN 2001el: Krisciunas et al. 2003, 2007; SN 2002bo: Benetti et al. 2004, Krisciunas et al. 2004c; SN 2003du: Leonard et al. 2005, Stanishev et al. 2007; SN 2004eo: Hamuy et al. 2006, Pastorello et al. 2007a; SN 2005cf: Pastorello et al. 2007b) and the available data have more than doubled in the past five years (Conley et al. 2006a). The rise time appears to be roughly 18 days, with some uncertainty whether there is a correlation with the light curve decline rate as well (e.g. Riess et al. 1999b, Contardo et al. 2000).

Overall, the following picture has emerged for SN Ia explosions. The emission of SNe Ia is powered by the stored energy in radio-active decays from ^{56}Ni through ^{56}Co to ^{56}Fe (Colgate & McKee 1969, Clayton 1974; see Kuchner et al. 1994 for an observational proof of this mechanism for SNe Ia). This release is moderated by the optical depth in the ejecta (Arnett 1982, Höflich et al. 1993, Pinto & Eastman 2000). Using Arnett's rule (Arnett 1982) one can derive the nickel mass from the observed luminosity at peak light (Arnett et al. 1985, Branch 1992, Vacca & Leibundgut 1996, Contardo et al. 2000, Stritzinger & Leibundgut 2005, Stritzinger et al. 2006). Not all Type Ia SNe produce the same amount of ^{56}Ni in the explosions (e.g. Cappellaro et al. 1997, Contardo et al. 2000, Stritzinger et al. 2006). Some objects are clearly subluminous, a signature that very little radioactive nickel is produced (most recent examples are SN 2002cx, SN 2003gq, SN 2005P and SN 2005hk; Jha et al. 2006b, Phillips et al. 2007). It has been speculated that they are deflagration explosions rather than delayed detonations. The derivation of the nickel mass based on Arnett's rule has been tested from explosion models, hydrodynamics and radiation transport calculations and has been shown to be reliable (Blinnikov et al. 2006).

The interpretation of the light curves has seen a revival in the past few years with attempts to explain the behaviour of the infrared light curves, in which a second maximum is observed (e.g. Elias et al. 1985, Meikle 2000, Krisciunas et al. 2003). The most convincing explanation is due to a temperature sensitivity of the emissivity between singly and doubly ionised iron-peak elements (Kasen 2006). Depending on the temperature decrease in the ejecta, the energy is released rapidly in the near-infrared and the secondary maximum is more or less pronounced. A similar argument for a temperature dependence in the SN Ia spectra had been made by Nugent et al. (1995) a decade earlier based on line ratios of Ca II and Si II.

Further dependencies on the amount of nickel synthesised in the explosion, the mixing within the ejecta and the progenitor metallicity exist (Kasen 2006). At the same time, these model calculations also predict a very narrow distribution of the near-IR peak luminosity (based on Chandrasekhar-mass models and a unique density structure of the ejecta), as it is observed (Krisciunas et al. 2004a). There are now hopes that the light curve width *vs.* luminosity relation of SNe Ia might be understood through a detailed exploration of the parameter space provided by current explosion models(Kasen & Woosley 2007).

At late times, the photometry and spectroscopy has been followed for several objects. Especially the addition of the infrared has provided new insights (Spyromilio et al. 2004, Sollerman et al. 2004, Stritzinger & Sollerman 2007). SNe Ia have IR light curves, which after the peak phase are nearly flat for several hundred days until the IR catastrophe sets in and the ejecta cool enough so that the energy is radiated in fine-structure lines in the thermal infrared rather than in the optical or the near-infrared (Fransson et al. 1996). As a consequence the IR contribution to the bolometric flux increases dramatically 300 days after the explosion. Derivations based simply on the V light curve (as sometimes employed in the past) are hence unreliable at these late phases. Also, the emerging flux is less than what is predicted assuming Arnett's rule to determine the nickel mass from the peak luminosity. This is a clear sign of $\gamma-$ray leakage from the ejecta and a signature of low-mass progenitor stars. The late decline rate of the light curves has been used by Stritzinger et al. (2006) to crudely determine ejecta masses from the bolometric light curves. The deviation of the decline rate from the expected decay rate of ^{56}Co is a signature of the losses due to the decreasing column density in the ejecta. Using a very simple model of the conversion of the $\gamma-$ray energy into the optical/IR wavelengths the derived ejecta masses all are well below the canonical Chandrasekhar-mass of the explosion models (Stritzinger et al. 2006). The reason for this discrepancy remains unclear, but could be due to asymmetries, i.e. dependencies on the viewing angle or a model that does not capture the relevant physics.

Another signature of variations in the explosions are spectro-polarimetric measurements which show that certain elements in the supernova ejecta are not distributed spherically (Wang et al. 2003b, Leonard et al. 2005, Chornock et al. 2006, Chornock & Filippenko 2007). A synopsis of the current situation is given by Wang et al. (2007). It appears that there is only a small asymmetry in the overall shape of the ejecta as the continuum polarisation appears generally low and in most cases below the detection limits. However, some stronger lines show a marked evolution in their polarisation indicating that the material is not evenly distributed throughout the ejecta and also giving clues on the possibly uneven burning process. There even appears to be a correlation between the degree of clumpiness and the luminosity of the supernovae with smaller polarisations observed for more luminous supernovae (Wang et al. 2007).

The spectroscopic evolution has also obtained a lot of attention in the past decade. Apart from some objects, which display truly different spectra (in particular the cases of SNe 1999aa (Garavini et al. 2004), 1999ac (Garavini et al. 2005, Phillips et al. 2006), 2000cx (Li et al. 2001), 2002cx (Li et al. 2003, Sollerman et al. 2004, Jha et al. 2006b), 2002ic (Hamuy et al. 2003, Kotak et al. 2004), and 2005hk (Jha et al. 2006b, Phillips et al. 2007) should be mentioned here), the general spectral evolution is characterised by different velocities at which the line absorptions are observed. Detailed analyses of the velocity shifts go back to Branch et al. (1988) and it is now established that most SNe Ia show high-velocity components in their spectra (Hatano et al. 2000, Mazzali et al. 2005). Observational trends appear to emerge in the way the velocities within the supernova ejecta evolve (Benetti et al. 2005), but the interpretation of these correlations are not clear yet. It is noteworthy that the distant objects appear to follow the general spectral evolution of their nearby counterparts and there is no obvious sign of differences in the spectral appearance of SNe Ia (Blondin et al. 2006, Garavini et al. 2007b). The interpretation of the spectra has now also been expanded to reconstruct the element distribution in the ejecta through the spectral evolution (Fisher et al. 1999, Stehle et al. 2005), which gives a direct input to the explosion models. Also, spectral calculations based on non-spherical ejecta are leading to new explanations for the luminosity and expansion velocity variations in SNe Ia (Kasen et al. 2006, Sim 2007, Sim et al. 2007).

The ideas on the explosion models have evolved only little in the past few years. The favourite mechanisms are the delayed detonation, in which an early deflagration (burning slower than the local sound speed) turns into a detonation (burning front moves supersonically) in the out layers (Khokhlov 1991, Röpke & Niemeyer 2007, Röpke et al. 2007), and pure deflagrations (see Hillebrandt & Niemeyer 2000 for a review of these models). Deflagrations in general are regarded as not providing enough energy for the brilliant displays of SNe Ia, however, in a few cases would a simple deflagration provide sufficient energy for a SN Ia (Blinnikov et al. 2006, Jha et al. 2006b, Phillips et al. 2007). There has been a lot of activity in extending the calculations into full three-dimensional simulations to explore the effects of asymmetries (Reineke et al. 2002, Gamezo et al. 2003, 2004, 2005, Röpke & Hillebrandt 2005, Röpke et al. 2006). The simulations are now also incorporating off-centre ignitions and other aspects, which could lead to non-uniform explosions (Sim et al. 2007).

Despite these advances, it remains to be understood, why SNe Ia can be calibrated with rather simple methods to provide accurate cosmological distances.

5 Cosmology with Supernovae

Cosmology with supernovae has developed over the second half of the last century. Various methods were devised to use supernovae to determine cosmological parameters ranging from simple standard candle paradigms to physical explanations of the supernova explosions and subsequent derivation of distances. The simplest use has been the determination of luminosity distances, i.e. the comparison of the observed flux to the total emitted radiation. A more elaborate method is the comparison of the angular diameter, through the measurement of the radial velocity of the expanding atmosphere, and the observed brightness. A critical assumption here is the sphericity of the explosion and the corresponding connection of the ejecta velocity and the luminosity, which has to be achieved through detailed emission models of the supernova explosion.

The classical parameters of observational cosmology, which govern the expansion of the universe in Friedmann-Robertson-Walker models, the Hubble constant H_0 and the deceleration parameter q_0, can be determined with accurate (luminosity) distances (Sandage 1961, 1988, Weinberg 1972, Peebles 1993, Peacock 1999). There is a rich literature on the Hubble constant and Type Ia supernovae (see Branch & Tammann 1992, Branch 1998, Leibundgut 2001, Perlmutter & Schmidt 2003 for reviews). The deceleration parameter has been replaced by more modern formulations specifically including the cosmological constant or some variants thereof (Carroll et al. 1992) and is generally referred to as 'Dark Energy.' Detailed theoretical descriptions are given in other articles of this issue.

5.1 The Hubble constant

5.1.1 Core-collapse supernovae

Following early work by Baade (1926), originally done for Cepheid stars, the expanding photosphere method (EPM; Kirshner & Kwan 1974, Schmidt et al. 1994, Eastman et al. 1996, Hamuy et al. 2001, Hamuy & Pinto 2002, Dessart & Hillier 2005) has been applied to several supernovae. The most comprehensive data sample has been assembled by Hamuy (2001). A critical test has become the distance to SN 1999em, which was determined through EPM (Leonard et al. 2001, Hamuy et al. 2002, Elmhamdi et al. 2003, Baron et al. 2004, Dessart & Hillier 2006) and which also has a Cepheid distance available (Leonard et al. 2003). The discrepancy in the distance determinations towards SN 1999em can be attributed to the fact that the correction factor for the dilution of the black body flux in EPM are strongly model dependent and need to be calculated for each supernova individually (Baron et al. 2004, Dessart & Hillier 2005).

Recently, Mario Hamuy has realised that the expansion velocity and the luminosity during the plateau phase correlate and that Type II SNe may be calibrated to become quite good distance indicators (Hamuy & Pinto 2002). The distance accuracy achieved this way can be better than 20%. These determinations are based on the physical understanding of the plateau phase of SNe II and are linked to physics of the supernova atmosphere. This means that they are independent of the *distance ladder*, which is the basis for the SNe Ia (see §5.1.2). Typical values for the Hubble constant from SNe II are in the range of 65 to 75 km s^{-1} Mpc^{-1} (Hamuy 2003).

A first attempt to derive the Hubble diagram with distant (up to z$\sim$0.3) SNe II using data assembled by the *CFHT* SN Legacy Survey has also been made recently (Nugent et al. 2006). Potentially, this method can independently check on the cosmic expansion history.

5.1.2 Type Ia supernovae

The best way to show that objects provide good relative luminosity distances is to plot them in a Hubble diagram. Originally, this diagram was using recession velocity *vs.* apparent magnitude (Hubble 1936, Sandage 1961). The underlying assumptions are that the Hubble law holds, i.e. the local expansion is linear, and that the objects are all of the same luminosity, i.e. standard candles, so that the apparent brightness directly reflects distance. Early versions of this Hubble diagram of SNe Ia showed that the peak magnitudes tracked the Hubble line fairly well (Kowal 1968, Tammann & Leibundgut 1978, Leibundgut & Pinto 1992), but considerable scatter was still present.

There are essentially three quantities that can be derived from such a Hubble diagram in the nearby universe: the slope of the expansion line, the scatter around the expansion line and the value of the local Hubble constant from the intercept at zero redshift (e.g Tammann & Leibundgut 1978, Leibundgut & Pinto 1992, Branch & Tammann 1992, Riess et al. 1996a, Branch 1998). The slope gives an indication of the local expansion field and for a linear expansion in an isotropic universe has a fixed value. The scatter around the expansion line provides a measure of the accuracy of the relative, in contrast to an absolute, distance determination, individual deviations from the smooth cosmological expansion and the measurement errors. The intercept of the line, finally, together with an estimate of the absolute (normalised) luminosity provides absolute distances and hence the Hubble constant. Recent Hubble diagrams of SNe Ia have been published by Tonry et al. (2003), Knop et al. (2003), Barris et al. (2004), Riess et al. (2004a,b), Astier et al. (2006), Wood-Vasey et al. (2007), Riess et al. (2007) and Jha et al. (2007). It should be noted that SNe Ia may be nearly standard candles in the near-infrared (Krisciunas et al. 2004a). The first significant IR sample shows very small scatter without prior correction for light curve shape.

Modern versions of this diagram have exchanged the recession velocity with the redshift, often corrected to the CMB rest frame and the distance modulus instead of the simple observed apparent peak brightness. It has become clear that SNe Ia are not simple standard candles (see §4, an extensive discussion is given in Leibundgut 2004). Hence, the distance has to be determined for each event individually, e.g. through the maximum luminosity *vs.* light curve width relation discussed in §4. Another option is to normalise the peak luminosities and to plot a 'corrected' apparent peak brightness, a method employed by the

Supernova Cosmology Project (e.g. Perlmutter et al. 1997, 1999, Knop et al. 2003). This approach is masking the importance of the light curve correction and also the importance of the absorption corrections.

The scatter of the normalised SNe Ia around the linear expansion line is less than 0.2 magnitudes or 10% in distance (Phillips et al. 1999, Jha et al. 1999, Tonry et al. 2003, Riess et al. 2004b, Jha et al. 2007; Fig. 2). Independent of our ignorance of the exact explosion mechanism or the radiation transport in the explosions this proves that SNe Ia can reliably be used as a (relative) distance indicator in the local universe and makes them empirically calibrated. This situation is very much comparable to the Cepheid stars, where the period-luminosity relation is based on empirical data from objects in the Magellanic Clouds.

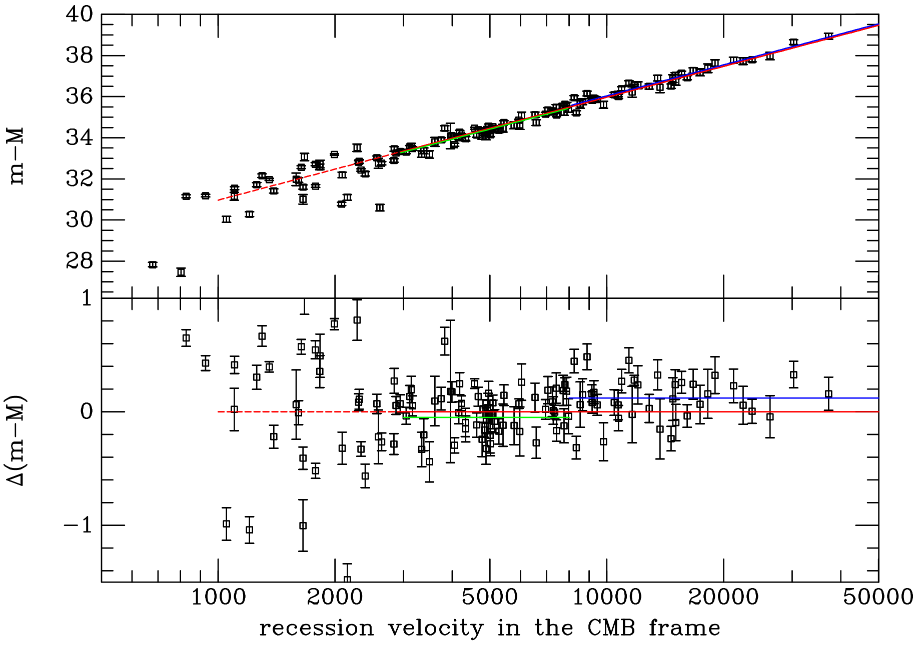

Figure 2: Hubble diagram of nearby Type Ia supernovae. The distances are derived from light curve shape corrected luminosities (data from Jha et al. 2007). Fits to different velocity ranges are shown. The red line is a fit to all SNe Ia with v>3000 km s^{-1} (extrapolated to lower velocities as a dashed line), the green line for the sample restricted to 3000 km s^{-1}<v<8000 km s^{-1} and the blue line for events with v>8000 km s^{-1}.

Fig. 2 displays the most recent, homogeneously treated sample of nearby SNe Ia from Jha et al. (2007). The upper panel displays the regular Hubble diagram with distance *vs.* recession velocity corrected to the rest frame of the cosmic microwave background, while the lower panel shows the data with the expansion field removed. This allows to appreciate the accuracy of the relative distances derived by the supernovae and also provides a better demonstration of the various cosmological models. This will become even clearer for the full Hubble diagram discussed below (Fig. 3). The distance modulus $(m - M)$ combines the observed magnitude with the observed flux F through

$$m = -2.5 \log(F) + const$$

and the absolute luminosity L of an object at the distance of 10pc

$$M = -2.5 \log(L) + const$$

and is determined for each supernova individually. The distance modulus describes the observed flux ratio of two objects at different distances according to the usual $1/\mathrm{D}^2$ law, which defines the cosmological luminosity distance and the observed flux with distance and emitted energy through

$$F = \frac{L}{4\pi D^2}.$$

For a linear cosmic expansion following Hubble's law

$$D = \frac{v}{H_0}$$

one expects that the distance moduli and the recession velocities are connected through

$$(m - M) = 5 \log(v) - 5 \log(H_0) + 25$$

where the velocity is measured in km s^{-1}, the distance in Mpc and the Hubble constant H_0 has units of km s^{-1} Mpc^{-1}.

It is obvious in Fig. 2 that below a recession velocity of about 3000 km s^{-1} the supernovae do not trace the smooth Hubble expansion, but the Hubble flow is heavily disturbed by motions due to the local matter distribution, often referred to as 'peculiar velocities.' These supernovae are regularly excluded from the cosmological studies. The slope above 3000 km s^{-1} is slightly larger, i.e. 5.22 ± 0.05, than the expected value for the linear expansion in the local universe, which could be an indication of evolution.

We demonstrate in Fig. 2 the effect of a possible change in the universal expansion rate at some distance from us. The lower panel shows the fits to data with $v > 3000$ km s^{-1}, a fit to the data in the range $3000 < v < 8000$ km s^{-1} and the data with $v > 8000$ km s^{-1}, where we force the fit for a linear expansion. The upper value was taken to be close to the reported outer edge of a possible 'Hubble bubble' (Zehavi et al. 1998, Jha et al. 2007) where the expansion inside is faster than outside and hence the true Hubble constant would be lower than what is determined locally. Indeed, there appears to be a shift by about 0.07 magnitudes (about 4% change in H_0) for the objects outside 8000 km s^{-1}. Another interpretation traces this change to an evolution in the intrinsic colours of SNe Ia (Conley et al. 2007).

By fitting the intercept of the expansion line a combination of the Hubble constant and the absolute luminosity is determined. Hence, for the derivation of the Hubble constant the (normalised) luminosity of the SNe Ia has to be known. The most direct way to achieve this is through the distance ladder and in particular the calibration of nearby SNe Ia by Cepheids (for the most recent results see Saha et al. 1999, Freedman et al. 2001, Sandage et al. 2006). The main discrepancy for the published values of the Hubble constant from SNe Ia is coming from the different interpretations of the Cepheids and application of the light curve shape correction. Ironically, the SNe Ia provide the best distance indicator beyond the Cepheid range and have replaced many rungs in the distance ladder making the Magellanic Clouds the last rung before cosmological distances. We do not quote a value for the Hubble constant here. The interested reader is referred to the papers mentioned above.

A different way to establish the Hubble constant with SNe Ia is through models. Originally tried by Arnett (1982) and Arnett et al. (1985) this has been further attempted by Leibundgut & Pinto (1992) and most recently by Stritzinger & Leibundgut (2005). In this case the absolute luminosity is derived from the amount of nickel produced in the explosion models and the derived luminosity, e.g. through Arnett's rule or direct radiation hydrodynamics calculations. Due to the range of observed SN Ia properties it is not possible to derive a value for the Hubble constant itself, but at least an interesting lower limit of $H_0 > 50$ km s^{-1} (3σ) could be derived by matching the faintest observed SNe with the largest imaginable nickel mass ($\sim$1 $M_\odot$) for the models. Overall, a slight inconsistency between the predications of the current models and the observations could be found. By adopting a Hubble constant of $\sim$70 km s^{-1} Mpc^{-1} one can derive a predicted range of nickel masses in the explosions ($0.5M_\odot < M_{Ni} < 1.0M_\odot$; Stritzinger & Leibundgut 2005).

5.2 The expansion history of the universe

Exploring the cosmic expansion rate over the history of the universe tells us about the changing contributions of the different matter/energy components of the universe (see the article by Linder). The supernovae provide an important information by mapping out the expansion history over a significant lookback time (out to a redshift of z$\sim$1.5, corresponding to a lookback time of about 2/3 of the age of the universe, or over 9 billion years for the concordance model and $H_0 = 70$ km s^{-1} Mpc^{-1}). It should be stressed that for the expansion history only relative distances are need to be measured. The SN Ia Hubble diagram of nearby objects (Fig. 2) gives ample empirical confidence that this can be achieved reliably.

The published distances of high-z supernovae are typically based on an *adopted* Hubble constant. Several theoretical papers in the recent past have made the mistake to include the Hubble constant as a free parameter in their fits. While this is okay to check that the marginalisation actually works correctly, claims that a specific value for the Hubble constant has been found are incorrect. The original papers all state very clearly what Hubble constant has been adopted for the study and people who use those data should be aware of this assumption.

The proposal to use supernovae to measure the cosmic deceleration goes back to Olin Wilson (1939) and was elaborated further by Tammann (1978) and Colgate (1979). one prediction made by these early visionaries was that time dilation would affect the observed light curves. This could finally be shown convincingly with the first distant SN Ia, SN 1995K, by Leibundgut et al. (1996) and was further confirmed on a large sample by Goldhaber et al. (1997, 2001). In the meantime this test has been performed following the detailed spectral evolution (Riess et al. 1997, Foley et al. 2005, Hook et al. 2005, Blondin et al. 2006, 2007). The predictions of a universal expansion have been confirmed in all cases ruling out alternative theories of "tired light."

Proposals to use SNe Ia to measure the expansion history of the universe go back into the late 1980s. The main goal at the time was to determine the mean matter density Ω_M to check the cosmological models. The first observational attempts were frustrated by lack of 'grasp,' i.e. the difficulty to cover large enough area on the sky to sufficient depths frequently enough. A search with the Danish 1.5m telescope on La Silla monitoring several fields once per month yielded only two distant SNe after two years. The follow-up spectroscopy was difficult to organise in a time before observatories were fully connected to the Internet and the information had to be transmitted through fax and telex, a particular problem for finding charts. The spectroscopic capabilities of the available 4m telescopes were marginal for the faintness of the objects (Nørgaard-Nielsen et al. 1989, Hansen et al. 1989, Schmidt et al. 1998, Riess et al. 1998). A large project to search for distant SNe Ia was initiated in the early 1990s in Berkeley (Perlmutter et al. 1991) and yielded first results on seven objects (several without spectroscopy and insufficient colour coverage Perlmutter et al. 1995). As a result the inferred cosmology was not correct (Perlmutter et al. 1997). The following years saw the emergence of vastly improved search techniques, the advent of 8m and 10m telescopes — greatly improving the quality of the spectroscopic confirmations, refined analysis methods taking many contaminating effects into account and the delivery of a surprise. With the proof of concept from the early searches the new projects, the Supernova Cosmology Project (Perlmutter et al. 1995, 1997, 1998, 1999, Knop et al. 2003, Hook et al. 2005) and the High-z Supernova Search Team (Schmidt et al. 1998, Leibundgut et al. 1996, Riess et al. 1997, 1998, Garnavich et al. 1998a,b, Riess et al. 2000, Coil et al. 2000, Tonry et al. 2003, Williams et al. 2003, Barris et al. 2004, Clocchiatti et al. 2006), started to provide astonishing evidence that the distant SNe Ia appeared fainter than predicted in a massless, empty universe. Early criticism of these results concentrated on difficulties with photometric accuracy of the faint sources, the treatment of the dust absorption in the host galaxy of the supernova, possible secular evolution of the supernovae over time, uncertainties in the normalisation of the peak luminosity of the SNe Ia and the, at the time still fairly small, sample size of distant objects, which could lead to sample biases or Malmquist effects (see Leibundgut 2001 for a summary of these early problems). Exotic possibilities, like unusual dust properties (Aguirre

1999a,b) were proposed or difficulties with the normalisation pointed out (Drell et al. 2000, Leibundgut 2000). Many of these difficulties have been addressed in the meantime. Also, the importance of the nearby SN Ia sample should not be underestimated. The reason that Riess et al. (1998) could find a signal for accelerated expansion with only 10 distant SNe Ia was largely due to the fact that an extensive, controlled, local sample of SNe Ia was at hand.

In the past few years the Canada-France-Hawaii Telescope *CFHT* Supernova Legacy Survey (SNLS; `http://www.cfht.hawaii.edu/SNLS/`) and the ESSENCE project (`http://www.ctio.noao.edu/wproject/`) have been collecting data of distant supernovae to measure the value of a constant equation of state parameter ω to 7% and 10% accuracy, respectively. The SNLS monitors four fields with the MegaCam instrument at the *CFHT* continuously, while ESSENCE uses the MosaicII camera with the CTIO 4m telescope during three months each year. The ultimate goals of these five-year projects are >700 SNe Ia for SNLS and >200 SNe Ia for ESSENCE. All supernovae must have a positive spectral classification to be included.

The SNLS has published cosmological results of their first year of observations based on 71 distant SNe Ia (Astier et al. 2006). The selection of the candidates and the spectroscopy of this project are described in Sullivan et al. (2006a), Lidman et al. (2005) and Howell et al. (2005). Other important results based on this extensive data set are a determination of the SN Ia rise time (Conley et al. 2006a), as well as the supernova rates and their connection to star formation in the host galaxy (Sullivan et al. 2006b, Neill et al. 2006). Further, this project obtained observations of a peculiar SN Ia possibly emerging from a super-Chandrasekhar-mass progenitor (Howell et al. 2006) and made a first measurement of distances at $z > 0.1$ of SNe II (Nugent et al. 2006).

The ESSENCE project is presented in Miknaitis et al. (2007) and the cosmological results based on the first three years including 60 SNe Ia are discussed in Wood-Vasey et al. (2007). All corresponding spectroscopy has been published (Matheson et al. 2005, Blondin et al. 2006, 2007). A first detailed description of photometry of a subset of the ESSENCE events observed with the Hubble Space Telescope (*HST*) pointed out some potential selection effects in the sample (Krisciunas et al. 2005). An evaluation of exotic proposals for dark energy when compared to the available SN Ia data was made in Davis et al. (2007).

A separate project including many ESSENCE members is the higher-z SN search with *HST*. The targets for this study have been SNe with z>1 (Strolger et al. 2004). These high-z supernovae have shown that the universe indeed was decelerating at z>1 and the acceleration phase has started only during the second half of the universal history (Riess et al. 2004a,b, 2007). The most recent data sample allowed Riess et al. (2007) to map out the change of the Hubble parameter over redshifts for the first time ever directly showing that the universal expansion rate has changed over time. This project also yielded important results on the evolution of the SN Ia rate as a function of redshift (Dahlén et al. 2004). However, the inference of long lead time before a SN Ia explosion has been disputed (Förster et al. 2006).

Other ongoing projects are the continuation of the Supernova Cosmology

Project (`http://panisse.lbl.gov/ACSclustersearch/`) to find supernovae in distant clusters with z>1. The goal is to observe SNe Ia in elliptical galaxies as the problem with the extinction in the host galaxy is strongly reduced. A first exploration of this method had been done by Sullivan et al. (2003). The claim has been made that SNe Ia in elliptical galaxies provide a cleaner sample. Possible problems with this approach is the lack of a good comparison sample of local supernovae. Data for a first object have recently been published exploring new ground-based observational methods, in particular adaptive optics imaging (Melbourne et al. 2007).

The extension of the Sloan Digital Sky Survey for a three-year supernova search is ongoing (`http://sdssdp47.fnal.gov/sdsssn/sdsssn.html`). The goal is to find 200 SNe Ia at 0.1<z<0.3. This project appears to be quite successful with many spectroscopically confirmed SNe Ia. An impressive mosaic is available from the above Web page and has been published in National Geographic Magazine. The local supernova searches have been described in §4. One should add here the SN Factory (`http://snfactory.lbl.gov/`), which is specifically set up to provide a large sample of nearby SNe Ia for the comparison with the high-z sample. So far only few events from this project has been published (Aldering et al. 2006, Thomas et al. 2007), all of peculiar nature.

The cosmological signal imprinted on the supernova data is modulated by several unwanted technical and astrophysical effects. At the basis is accurate photometry (Stubbs & Tonry 2006). While this sounds like a trivial statement, it has become difficult to free the measurement from all the effects of Earth's atmosphere to the percent level required for the SN light curves. Improvements in the instrumental characterisations are made continuously (Miknaitis et al. 2007), but one of the limiting effects are the implementation of the various filter pass bands at the telescope, which has to be known accurately to be able to combine observations from different telescopes (Davis et al. 2006). For nearby supernovae this led to the introduction of an empirical correction (often referred to as S-correction) of data sets from different telescopes (Stritzinger et al. 2002). As a consequence recent projects concentrate on single instruments (*CFHT*/MegaCam for the SNLS and CTIO Blanco telescope/MosaicII for ESSENCE) for the photometry to avoid this problem. Nevertheless, it still remains difficult to combine SNLS and ESSENCE data for a joint analysis as done in Wood-Vasey et al. (2007), Riess et al. (2007), Davis et al. (2007) and various other publications.

Since the supernovae have to be corrected for foreground extinction the colour needs to be measured as accurately as possible. Any uncertainty in this respect is multiplied by the absorption correction. The uncertainty of the colour measurement also has a direct influence on the K-correction (Hamuy et al. 1993, Kim et al. 1996, Nugent et al. 2002, Hsia et al. 2007). The observed photometry has to be translated into the supernova rest frame and hence any redshift of the spectrum needs to be taken into account (see Jha et al. 2007 for a detailed description of this problem and a current implementation). The K-corrections are time-dependent and need to be calculated for the correct phase as well as the correct intrinsic colour. This intimately connects the K-corrections with the absorption correction and modern versions of light-curve fitting programmes for distant supernovae merge this evaluation. The light curve fitting methods and calibration are critical to the supernovae cosmology and it should be emphasised that depending on which methods are used, the derived distances can change – sometimes in a systematic way. Wood-Vasey et al. (2007) have performed a detailed analysis of the SNLS/SALT fitter (Guy et al. 2005) and MLCS2k2 (Riess et al. 2004b, 2007, Jha et al. 2007) and confirmed that consistent cosmological results are derived by the two methods on the same data sets, but small differences remain.

Detailed spectroscopy certainly would help, but the signal achieved with the current telescopes is still limited and in many cases the supernova spectrum is contaminated by host galaxy light. Methods to separate the SN spectrum from the galaxy are either to try a deconvolution (Blondin et al. 2005) or subtract a scaled galaxy spectrum (Sainton 2004, Howell et al. 2005). The spectroscopy is also essential to distinguish SNe Ia from luminous SNe Ib/c as the two classes stem from distinct explosion mechanisms and confusion could lead to wrong conclusions, when the objects are not separated correctly (Homeier 2005, Tautenberger et al. 2006).

Astrophysical effects, which can influence the cosmological interpretation of supernova data include absorption in the Milky Way and in the host galaxy, gravitational lensing, evolution of the supernovae as a function of age of the universe, e.g. due to different metallicity, selection biases due to limiting sampling of the intrinsic supernova distribution and effects from a local underdensity, which would mean that the local expansion rate is lower than the global one ('Hubble bubble').

Several of these are well under control. Gravitational lensing does not appear to be a major issue for the redshifts considered so far. The highest redshift supernovae may be affected by lensing individually, but the overall effect should be minimal (Wambsganss et al. 1997, Holz & Wald 1998, Amanullah et al. 2003, Gunnarsson et al. 2006, Jönsson et al. 2006, 2007). The absorption due to dust in our own Milky Way is also fairly easily corrected. The effect is somewhat alleviated by the redshift and the diminished influence of dust absorption at redder wavelengths. Evolution of the supernova peak luminosity could mimic a cosmological effect, but the available data do not indicate any significant changes between the local and distant SN Ia samples. Within the achievable accuracy the distant supernovae appear the same spectroscopically (Hook et al. 2005, Lidman et al. 2005, Matheson et al. 2005, Blondin et al. 2006, Riess et al. 2007) and also their light curve behaviour appears rather similar to the local sample (Astier et al. 2006, Wood-Vasey et al. 2007). The effect of the metallicity of the progenitor star is predicted to be insignificant (Röpke & Hillebrandt 2004).

Our deductions on cosmology and dark energy could be severely hampered by the limited accuracy with which we know the local expansion field (see §5.1.2, Hui & Greene 2006, Cooray & Caldwell 2006, Jha et al. 2007), selection biases which skew the observed distribution from the intrinsic one (Leibundgut 2001, Wood-Vasey et al. 2007), and our lack of a good understanding of the dust properties in the host galaxies (Elias-Rosa et al. 2006, Astier et al. 2006, Wood-

Vasey et al. 2007).

As already shown in §5.1.2 the local expansion field is not smooth and local flows are distorting our ability to set the zero-point for the expansion rate. This leads to a systematic uncertainty, which needs to be overcome, if more accurate determination of cosmological parameters will be attempted. The effect is of the order of about 6 to 8% overall (Jha et al. 2007, Wood-Vasey et al. 2007). Larger nearby supernova samples are required to evaluate the reality of a Hubble bubble. Another possibility is to improve our knowledge of the density distribution in the local universe (as attempted over a decade ago, e.g. Bertschinger et al. 1990, Blakeslee et al. 1999) for a better understanding of the local disruption of the smooth universal expansion. With very large samples of nearby supernovae one could attempt to map this density field as well, but that will likely require several thousand supernovae.

The problem can of course also be inverted and the SNe Ia be used to determine the local velocity field compared to the CMB. This has been done with early samples by Riess et al. (1995) and more recently by Haugbølle et al. (2007) who find a quadrupole in the velocity distribution.

Ideally one would like to use distance limited supernova samples. With a hypothetical standard candle, which has a narrow luminosity function, one would hope that a flux limited sample would also be volume limited. There are several reasons why the available distant supernova samples are not volume limited. First, the SNe Ia are not standard candles and their luminosity function is spanning almost a factor of 10 from the brightest to the faintest events. Even though the most extreme cases are not included the most distant supernovae are also the most luminous ones (Krisciunas et al. 2005). Second, supernova searches all use a certain frequency, with which the search fields are monitored. This means that a supernova is discovered during its rise and depending on the distance and the weather conditions objects will be lost (Miknaitis et al. 2007). Finally, dust absorption in the host galaxy will dim some events, hence make them too faint to be discovered and remove them from the sample. A priori this would seem not such a problem, but it turns out that for more distant objects this becomes progressively more important and together with the limited sampling frequency creates a systematic bias. Wood-Vasey et al. (2007) have simulated this effect in detail for the ESSENCE data set and found a considerable bias (nearly 0.3 magnitudes in distance modulus at z=0.6), if the default absorption prior was used. They introduced separate, redshift dependent priors for the ESSENE data to correct for the fact that more SNe Ia go undetected at higher redshift and larger host galaxy absorption. The classical Malmquist bias is here mixed together with the assumption on the intrinsic colours of the supernovae and the absorption in their host galaxies.

The unknown reddening law in external galaxies is a further uncertainty, which systematically limits our ability to determine cosmological parameters. Light scattering depends on the physical size of the dust particles. So far the local absorption law has been assumed for all supernovae, but it has been shown that for many heavily extincted SNe Ia a different reddening law seems to apply (Riess et al. 1996b, Krisciunas et al. 2000, Elias-Rosa et al. 2006, Astier et al.

2006). The curious fact is that with the regular colour dependence a colour excess, i.e. an apparent redder colour due to the interstellar dust scattering, is rather large for bluer bands. The canonical value for the solar neighbourhood is about 3.1 for the visual V band. For many SNe Ia this value appears to be reduced to somewhere between 2 and 3. This has also the curious effect that the absorption correction for some supernovae is reduced and the scatter in the distances reduced. However, once the reddening law is a free parameter it can be assumed that it will be vary for different sight lines through distant galaxies. This will introduce a random scatter, which will be very difficult to overcome. For the ESSENCE supernovae, these combined colour effects constitute the largest uncertainty (about 10% overall; Wood-Vasey et al. 2007).

These last uncertainties will not easily be remedied by larger samples. They present fundamental shortcomings of our understanding of some of the critical items in supernova cosmology. They are not directly related to the supernova physics itself, but are an expression of the fact that the universe is filled with clumped matter, dark and baryonic, which distorts our position as a fair observer of the universe and affects the light we observe of these distant objects. Overcoming these systematic difficulties will be key to further improve the accuracy with which we can determine the cosmological parameters.

Figure 3 displays the latest data set, which is a combination of the largest nearby SN Ia sample from Jha et al. (2007), the ESSENCE data (Wood-Vasey et al. 2007) and the published SNLS (Astier et al. 2006). The data are remarkably consistent with the concordance model of $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

The SNe Ia are further used to determine the integral of the equation of state parameter ω over the observed redshift range (z<1.7). All experiments find a consistent value of $\omega = -1$ within the uncertainties. Currently these are of about 13% statistical and 13% systematic for ESSENCE (Wood-Vasey et al. 2007) and 9% statistical and 5% systematic for SNLS (Astier et al. 2006). These values are unfortunately not directly comparable as different assumptions went into the calculations of the errors. Nevertheless, all results so far are consistent (within 1 σ) with a cosmological constant. An important ingredient in this derivation is the matter density, which in most recent studies has been taken from the baryonic acoustic oscillation measurements of Eisenstein et al. (2006) or Cole et al. (2005). The accuracy of the derivation of ω strongly depends on how well the matter density Ω_M can be constrained. Sometimes a flat geometry of the universe is also assumed.

Attempts have been made to derive constraints on a possible time dependence of ω using the supernova data. One should caution these enterprises as they are based on data, which are most likely not accurate enough to warrant such analyses. Most published attempts demonstrate this fairly clearly as the parameters become essentially unconstrained (Riess et al. 2004b, Wood-Vasey et al. 2007, Riess et al. 2007). Several theoretical papers have further ignored the systematic uncertainties in the data and may have derived spurious results.

One other interesting application of the Hubble diagram of SNe Ia is the attempt to constrain any change of Newton's gravitational constant G. The

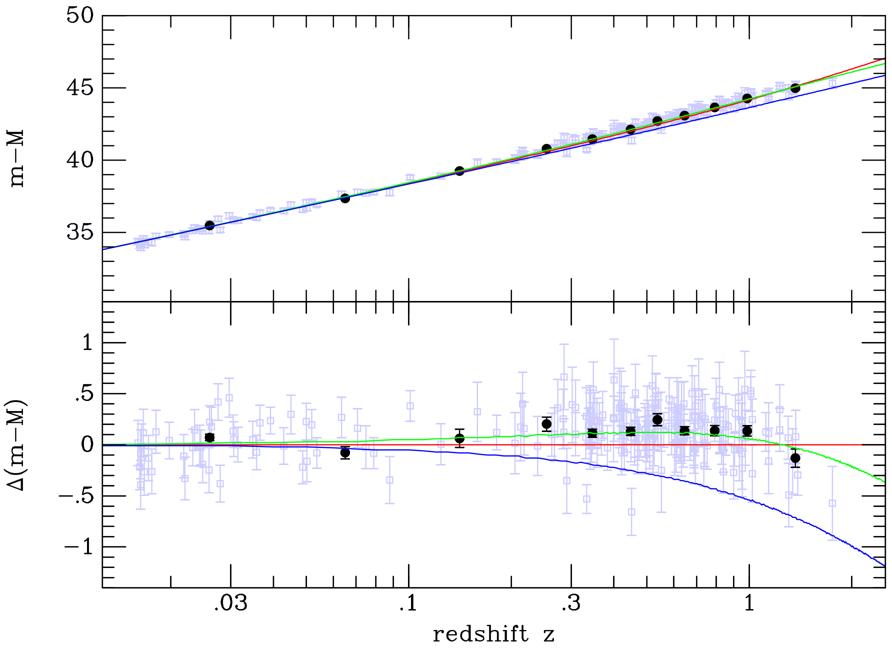

Figure 3: Hubble diagram of Type Ia supernovae. The distances are derived from light curve shape corrected luminosities (data from Davis et al. 2007). The red line is for an empty universe ($\Omega_\Lambda = \Omega_M = 0$), the blue line for an Einstein-de Sitter model ($\Omega_\Lambda = 0, \Omega_M = 1$). The concordance model ($\Omega_\Lambda = 0.7, \Omega_M = 0.3$) is shown as the green line fitting the data best. The bottom panel shows all distances relative to the empty universe model. The data for the individual supernovae is plotted as shaded point, while the binned data are shown in black.

current limits exclude changes larger than $|\frac{\dot{G}}{G}| < 2.9 \cdot 10^{-11}$ year^{-1} (Gaztañaga et al. 2002, Lorén-Aguilar et al. 2003, García-Berro et al. 2007).

6 Outlook and future projects

SNe Ia are amongst the most promising candidates to further improve our view of the cosmos. They appear prominently in the recent studies on how dark energy could be further constrained (Albrecht et al. 2006, Peacock et al. 2006). Together with other probes of the deep universe the SNe Ia should help us to characterise dark energy and possibly discover its nature.

Several projects have been proposed. The next surveys require new instrumentation, in particular wide-field cameras and dedicated telescopes. The SNLS has already shown the way forward with its allocation of several hundred nights on a single telescope. The next step is the Dark Energy Survey (`http://www.darkenergysurvey.org/`) planned with the CTIO Blanco 4m telescope. For this project a new camera is being built for this telescope.

The goal is to observe 2000 SNe Ia with $0.3<z<0.8$. Future survey telescopes like the Large Synoptic Survey Telescope (*LSST*; `http://www.lsst.org`) or The Panoramic Survey Telescope & Rapid Response System (*Pan-STARRS*; `http://pan-starrs.ifa.hawaii.edu/public`) will find thousands of supernovae. It will become impractical to obtain spectroscopy for all these objects for the classification and statistical approaches using the observed light curve shapes and the colours are being developed (e.g. Barris & Tonry 2004, Riess et al. 2004b, Sullivan et al. 2006a, Conley et al. 2006b, Kuznetsova & Connolly 2007). However, it still needs to be demonstrated that such large samples will allow us to improve the cosmological parameters.

An important extension of the current supernova work is towards higher redshifts. The sample of known SNe Ia at $z>1$ is very small still (Riess et al. 2007) and these events help significantly to constrain the cosmological models and also to check for systematic effects in the supernovae. All these very distant SNe Ia have been found by *HST* and its large area Advanced Camera for Surveys *ACS*. This is one reason why future space projects aim at wide field imaging. The synergy with weak lensing studies are obvious and strong science drivers for these missions have been developed. The best know proposal is the SuperNova Acceleration Probe (SNAP; `http://snap.lnbl.gov`), which has stimulated many interesting studies of what could be achieved by such a data set. Currently the SNAP satellite could reach SNe Ia out to $z\approx1.5$. Three missions have been selected for a study as a Joint Dark Energy Mission (JDEM) between NASA and the US Department of Energy. They are the Advanced Dark Energy Physics Telescope (ADEPT), the Dark Energy Space Telescope (Destiny; `http://destiny.asu.edu`) and SNAP. All of them employ the supernova Hubble diagram in addition to weak lensing surveys to further characterise dark energy.

To overcome the difficulties with the optical colours it has been suggested to construct a supernova Hubble diagram in the near infrared. At these wavelengths the SNe Ia are showing very small scatter in their peak luminosity and promise to approach the standard candle concept better than at the blue wavelengths employed so far (Krisciunas et al. 2004a). The difficulty so far has been that due to the redshift the rest frame near-infrared wavelengths are pushed to wavelengths were not enough sensitivity is available. With the future *JWST* and its infrared capabilities it will be possible to compile a Hubble diagram of distant SNe Ia in the near infrared. This will present a critical test of the current results and may significantly improve the distance accuracy as several limiting effects, like light curve shape and reddening corrections can be avoided. A first attempt of a Hubble diagram in the I pass band has been made by Nobili et al. (2005).

An independent test of the cosmology will come from an extended Hubble diagram of type II supernovae. These distances are based on completely different physical assumptions. Work in this direction has started (Nugent et al. 2006).

Further improvements will come from a better understanding of the explosions themselves. The question whether the distant SNe Ia are identical to the ones observed locally has not been fully addressed. The currently available observational resources do not allow us to obtain data of the required quality to compare, e.g., the spectral evolution of the distant supernovae. With a secured model for the explosion, it will become easier to explore possible systematic differences of supernovae coming from younger progenitor systems than older ones. There have been discussions of differences between supernovae coming from presumably different parent populations, e.g. SNe Ia in spiral galaxies and elliptical galaxies, which might be from slightly different progenitor systems, but it is too early to draw conclusions. The key to solving this question lies with observations of local SNe Ia. These objects can be observed with sufficient detail that we can explore the different explosion models and possible progenitor channels, which lead to the explosions.

7 Conclusions

Supernovae have been one of the main reasons, why we now consider a dark energy component for the universe. These explosive events have proved to be ideally suited for cosmological distance measurements. Their variability, often regarded as detrimental by placing severe observational constraints, has turned into an advantage. The brightness evolution allows us to identify these cosmic light houses, and, with sufficient knowledge of their intrinsic properties, we can correct for various astrophysical effects, which could compromise the cosmological deductions.

Understanding the physics of the explosions remains a prime task. Core-collapse supernovae have a relatively simple radiation transport and can be used to derive fairly accurate distances in the local universe. Core-collapse supernovae are fascinating events, which also tell us about the stellar evolution of massive stars, how they shape their environments through winds and how companions can change their surface evolution, while the stellar core evolves towards the collapse. Since at least some $\gamma-$ray bursts also show signatures of supernovae, it is important to understand this supernova class better. Through a modified expanding photosphere method they will continue to provide further constraints on the Hubble constant. The physical nature of this measurement is very attractive as it bypasses the usual distance ladder. By expanding to higher redshifts an independent confirmation of the accelerated expansion will become possible. This method is observationally and theoretically expensive requiring multi-band photometry and spectroscopy at several epochs and tailored simulations of the spectra to match the observations. Nevertheless, the effort should be continued as it appears at the moment to be the only distance measurement to individual events to complement the thermonuclear supernovae.

Thermonuclear supernovae have spectacularly changed our view of the universe. Empirically calibrated they have proved to be excellent distance indicators. The fact that many questions regarding the exact explosion mechanism and the as yet uncertain progenitor systems remain has not hindered their use for cosmology. There is significant progress in both areas. At the moment a consensus on these questions, however, still remains to be found. The past decade has seen SNe Ia take centre stage for the derivation of cosmological parameters. While they have been a favourite for the determination of the Hubble constant for several decades, the difficult calibration of their absolute luminosity at maximum has hampered their ability to determine an accurate value free of systematics. With the exquisite capability of SNe Ia to deliver relative distances the problem of the Hubble constant rests with an accurate calibration through other distance indicators, e.g. Cepheid stars.

A beautiful confirmation of general relativity as the basis for the cosmological model is the demonstration of time dilation in the light curves and the spectral evolution of SNe Ia. SNe Ia discovered the accelerated cosmic expansion and hence provided support for an additional energy component of the universe. They now supply strong evidence for a cosmological constant. The most recent supernova surveys, based on over one hundred events, have not shown any significant deviations from an integrated equation of state parameter $\omega = -1$. One should, however, caution against any attempts to over-interpret the current data. Exploring a time-variable ω should be done with the current limitations of the data in mind. The accuracy required to significantly constrain $\omega(t)$ is probably beyond what is currently available.

Several systematic effects are still of concern for this determination. The statistical uncertainties have reached the level of these systematics and simply increasing the sample size beyond what will be become available through SNLS and ESSENCE (several hundred SNe Ia beyond $z>0.3$) will not improve on the result any longer. Detailed understanding of the various astrophysical effects, which have to be treated to extract the cosmological signal, has now become imperative. The physical nature of the light curve shape *vs.* peak luminosity relation, the intrinsic colour variations among SNe Ia, the influence of dust absorption in the host galaxies, evolutionary trends in SNe Ia as a function of redshift and the selection biases of the searches need to be examined carefully. The limitations in accurately determining the local expansion rate are now also becoming a significant weakness. The latter is an obvious demonstration of the importance of the local SNe Ia. They provide the zero-point against which the distant supernovae are compared for the cosmology.

It is hence clear that an improved local sample of SNe Ia will provide several avenues for future improvements on the determination of the dark energy parameters. In addition, supernovae projects extending to higher redshifts and into the infrared hold great promise to overcome the systematic problems encountered at the moment.

Supernovae are one of the prime candidates to describe the characteristics of dark energy. With the lack of a clear theoretical contender for this unknown component, observations exploring the effects of dark energy are decisive and hopefully will lead us eventually to understand the properties of dark energy.

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