Type Ia Supernovae

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Abstract

Type Ia Supernovae are in many aspects still enigmatic objects. Their observational and theoretical exploration is in full swing, but we still have plenty to learn about these explosions.

Recent years have already witnessed a bonanza of supernova observations. The increased samples from dedicated searches have allowed the statistical investigation of Type Ia Supernovae as a class. The observational data on Type Ia Supernovae are very rich, but the uniform picture of a decade ago has been replaced by several correlations which connect the maximum luminosity with light curve shape, color evolution, spectral appearance, and host galaxy morphology. These correlations hold across almost the complete spectrum of Type Ia Supernovae, with a number of notable exceptions. After 150 days past maximum, however, all observed objects show the same decline rate and spectrum.

The observational constraints on explosion models are still rather sparse. Global parameters like synthesized nickel mass, total ejecta mass and explosion energetics are within reach in the next few years. These parameters bypass the complicated calculations of explosion models and radiation transport. The bolometric light curves are a handy tool to investigate the overall appearance of Type Ia Supernovae. The nickel masses derived this way show large variations, which combined with the dynamics from line widths, indicate that the brighter events are also coming from more massive objects.

The lack of accurate distances and the uncertainty in the correction for absorption are hampering further progress. Improvements in these areas are vital for the detailed comparison of luminosities and the determination of nickel masses. Coverage at near-infrared wavelengths for a statistical sample of Type Ia Supernovae will at least decrease the dependence on the absorption. Some of the most intriguing features of Type Ia Supernovae are best observed at these wavelengths, like the second peak in the light curve, the depression in the J band, and the unblended [Fe II] lines in the ashes.

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Contents

1 Introduction

The interest in supernovae has risen dramatically with their application to cosmological problems. Their unique capabilities as distance indicators on the cosmic scale have pushed them into the limelight of cosmology. These objects, however, are interesting and exciting in their own right. Supernova physics relates some of the most complicated physical processes from the explosion mechanisms to nucleosynthesis, radiation transport, and shock physics as well as some of the most intriguing astrophysics ranging from star formation and stellar evolution to cosmic metal enrichment, evolution of galaxies, and the scale and fate of the universe. Their brightness makes them ideal *stellar* tracers at large distances and look back times. Solving some of the supernova specific problems will hence give us clues on a much larger scale.

Stellar explosions have been observed for many centuries. Nonetheless, supernovae are extremely rare and only six of them have been observed over the last millennium in our own Galaxy (Clark & Stevenson 1977, Murdin & Murdin 1985, van den Bergh & Tammann 1991). The number of extragalactic supernova detections has grown continuously.

Originally only searched by a few limited experiments (e.g. Zwicky 1965) with about a dozen SNe detected each year, the topic has taken a big turn with SN 1987A and the emergence of deep coordinated searches for distant supernovae in the last decade. There are now nearly 200 SNe detected each year (cf. IAU Central Bureau for Astronomical Telegrams[1], Asiago Supernova Catalog[2] (Barbon et al. 1999), Sternberg Astronomical Institute Supernova Catalog[3] (Bartunov & Tsvetkov 1997)). This plethora of objects has revealed an increasing number of peculiar, i.e. not easily classified, supernovae. On the other hand, it has allowed us to conduct detailed studies of specific supernova classes and find the commonalities as well as the individuality among supernovae. The surge of data has further provided many new constraints for the models.

It has become increasingly clear that two main classes of supernovae (Type Ia *vs.* Type II and Type Ib/c) with physically completely different backgrounds exist. Originally an observational separation according to spectral features (Minkowski 1941, 1964, Harkness & Wheeler 1990, Filippenko 1997a) the classification scheme has proven to identify physically distinct objects. On the other hand, the classification system has not turned out to be sufficient. Several objects defy a clear classification and have forced extensions to the system. There is, however, a move to a more physical description of individual objects. Especially bright, well-observed, events have increased our understanding of the explosions.

Type Ia Supernovae (SNe Ia) are now almost universally accepted as thermonuclear explosions in low-mass stars (Trimble 1982, 1983, Woosley & Weaver 1986). All other known supernova explosions are thought to be due to the core collapse in massive stars.

There are many reviews on (Type Ia) Supernovae available. The most comprehensive books are Petschek (1990), Wheeler, Piran, & Weinberg (1990), Woosley (1991), McCray & Wang (1996), Bludman et al. (1997), Ruiz-Lapuente et al. (1997), Niemeyer & Truran (1999), and Livio et al. (2000). Excellent reviews were given by Trimble (1982, 1983) and Woosley & Weaver (1986). More recent monographs on Type Ia in general are Wheeler et al. (1995) and Filippenko (1997b). Possible progenitor systems (Branch et al. 1995, Renzini 1996, Livio 1999), supernova classifications (Filippenko 1997a), supernova rates (van den Bergh & Tammann 1991), the Hubble constant from SNe Ia (Branch 1998) and the status of explosion models (Hillebrandt & Niemeyer 2000) are covered in more specific reviews.

1.1 Classification

Supernovae are classified by their spectrum near maximum light (see Filippenko 1997a for a review on supernova classifications). The Type Ia Supernovae are characterized by the complete absence of hydrogen and helium lines and a distinct, strong absorption line near 6100Å, which comes from a doublet of singly ionized silicon with $\lambda\lambda$6347Å and 6371Å. Hydrogen or helium lines never appear in the spectra of SNe Ia at any phase of the evolution. Significant variations have been observed within this scheme, but in general SNe Ia can safely be distinguished from any other supernovae (Filippenko 1997a). Great care has to be taken to separate the SN Ia from SNe Ib/c which can display a similar

[1] `http://cfa-www.harvard.edu/cfa/lists/Supernovae.html`

[2] `http://merlino.pd.astro.it/~supern`

[3] `http://www.sai.msu.su/cgi-bin/wdb-p95/sn/sncat/form`

spectrum at early phases.

Secondary classification criteria are the late-phase spectrum dominated by forbidden iron and cobalt lines, light curve shape, color evolution, and host galaxy morphology. None of these is sufficient by itself, but may provide additional evidence for a classification.

1.2 Astrophysical importance

Since SNe Ia are possibly the main producer of iron in the universe, they provide a clock for the metal enrichment of matter. The relative long progenitor life times, as compared to massive stars which become core-collapse supernovae, provides a convenient feature in the relative metal abundances of $\alpha-$elements and iron-group elements (Renzini 1999).

The heating of the interstellar medium, in particular for elliptical galaxies, depends on the SN Ia rates and their energy input (Ciotti et al. 1991).

As explosions of white dwarfs SNe Ia are placed at the end of one of the major stellar evolution channels. Although only a few white dwarfs really explode as SNe Ia, they still can provide important information on the binary fraction of stars and the evolution of binary systems both in our Galaxy (e.g. Iben & Tutukov 1994, 1999) and as a function of look back time (Yungelson & Livio 1998, Ruiz-Lapuente & Canal 1998).

Supernovae also play an important feedback role during the early galaxy evolution and might be responsible for substantial loss of material from galaxies (e.g. Wyse & Silk 1985, Burkert & Ruiz-Lapuente 1997, Ferrara & Tolstoy 2000) and the regulation of the star formation process. The contribution of SNe Ia as opposed to core-collapse supernovae from massive stars is, however, unclear.

1.3 Type Ia Supernovae and Cosmology

Recent years have seen SNe Ia taking center stage in observational cosmology. As the momentarily best distance indicator beyond the Virgo cluster, they provide the main route to the current expansion rate (Branch 1998) and the deceleration of the universe (Riess et al. 1998a, Perlmutter et al. 1999). Almost all Hubble constant determinations are now involving SNe Ia in one form or another. Two large HST programs have adopted SNe Ia as their prime distance indicator beyond the reach of Cepheid stars (Saha et al. 1999, Gibson et al. 2000, Mould et al. 2000). Although other secondary distance indicators are still discussed, in most approaches they enter the analyses with lower weight (Mould et al. 2000). It is also gratifying to see that a general convergence of the value of H_0 to within the respective error bars between 60 and 70 km s^{-1} Mpc^{-1} has been reached.

The claim, based on SNe Ia, for an accelerated universe (Riess et al. 1998a, Perlmutter et al. 1999) has triggered an enthralling debate in cosmology. It will be an important next step to verify that supernova evolution is not mimicking a signal which has been interpreted as a cosmological constant. Other explanations of the supernova result apart from a cosmological constant and based on decaying particle fields have been proposed as well (for a recent review see Kamionkowski & Kosowsky 1999).

2 Observational characteristics

Type Ia supernovae are characterized by the absence of hydrogen and helium and the presence of processed material, mostly calcium, silicon and sulphur, in their spectra during the peak phase. At late phases the spectrum is dominated by emission lines of iron-group elements.

SNe Ia further exhibit a distinct light curve shape, extreme luminosity, absence of any appreciable amount of circumstellar material, and a lack of detectable polarization.

2.1 Observational material

Recent years have seen a major increase in reliable SN Ia data at all wavelengths. The large collection of optical data from the Calán/Tololo Supernova Survey (Hamuy et al. 1995, Hamuy et al. 1996c) has superseded the older, inhomogeneous catalogs (Barbon et al. 1973a, Leibundgut et al. 1991a). The Calán/Tololo survey has delivered 29 SNe Ia with at least one classifying spectrum and light curves in BVI. At the same time, many nearby supernovae have been observed with modern methods (reference lists can be found in Filippenko 1997a, Branch 1998, Contardo et al. 2000). Of particular interest are also the new observations of SN 1997br (Li et al. 1999), SN 1997cn (Turatto et al. 1998) and SN 1998bu (Suntzeff et al. 1999, Jha et al. 1999, Hernandez et al. 2000). A catalog of SN Ia observations has been published by Riess et al. (1999a) summarizing the data collection of 22 SNe Ia in $BVRI$.

Currently there are a number of supernova searches under way which will produce more densely sampled light curves and spectroscopic evolutions. Data are collected in a systematic way at several places. A large program of supernova observations has been ongoing at Asiago (Barbon et al. 1993) for many years. Bright supernovae are regularly observed in $BVRI$ and optical spectroscopy. The group at the Center for Astrophysics is collecting data on most bright new supernovae. In addition to the published data (Riess et al. 1999a, Jha et al. 1999) several more SNe Ia have been observed in $BVRI$ and occasionally in U. For a few objects also JHK light curves are being assembled. The robotic telescope at Lick Observatory (Richmond, Treffers, & Filippenko 1993) is now discovering new supernovae routinely. These objects are then followed in $BVRI$ and with spectroscopy. The Supernova Cosmology Project (e.g. Perlmutter et al. 1997, 1999) has started to search for nearby SNe Ia to supplement the currently existing sample. In a massive search and follow-up program involving observatories around the globe many objects will be observed extensively in $UBVRI$ and with optical spectroscopy in the next few years. The Mount Stromlo and Sidings Springs Abell Cluster Search has found around 50 supernovae (Reiss et al. 1998). The light curves from this search are a combination of very wide filters (the Macho V_M and R_M filter set, cf. Germany et al. 1999) and regular $BVRI$ observations. Only a fraction of the objects has a spectroscopic classification. So far 6 SNe Ia have been reported (Reiss et al. 1998). A follow-on project to the Calán/Tololo Supernova Survey has been initiated recently, which concentrates on finding bright SNe Ia and follow them in $UBVRIJHK$ and spectroscopy. Infrared photometry and spectroscopy has regularly been obtained at UKIRT and the IRTF (Spyromilio et al. 1992, Meikle et al. 1996, Bowers et al. 1997, Meikle & Hernandez 1999, Hernandez et al. 2000).

Many observations are also obtained by amateur astronomers. Collaborative efforts are undertaken by the International Supernova Network[4], the Variable Star Network[5] (VS-NET), and through the Astronomy Section of the Rochester Academy of Sciences[6]. The collaboration between professional and amateur astronomers is becoming a very valuable extension of supernova research. The combination of observations from all sources has played an important role in some of the recent research projects (e.g. Riess et al. 1999b).

2.1.1 SN Ia Rates

The frequency of supernovae carries important information about their parent population and the physical process which drives the explosions. Although the relative importance of this measurement has been recognized, it has been very difficult to derive good numbers for the supernova rates (for reviews see van den Bergh & Tammann 1991, Tammann 1994, Strom 1995). The main problem is the extreme rarity of supernovae which makes statistically significant samples very difficult to come by. The problem worsens when the rates are split into many supernova and galaxy subtypes leaving very few objects per sampling bin. The searches have further to consider the time for which supernovae could have been discovered. The control time is an important parameter which is typically difficult to calculate as it depends on light curve shape, absolute luminosity, and the absorption by dust in the local supernova environment (Tammann 1994, Strom 1995). Supernova rates are normally expressed as the number of supernovae per century per blue unit (i.e. solar) luminosity (typically per $10^{10}\mathrm{L}_{B_\odot}$). The latter reflects the belief that supernovae are linked to the stellar population which dominates the galaxy light. The attempt to measure the SN Ia rate per H luminosity, which traces older stellar populations, seems more reasonable (van den Bergh 1990), if we believe that SNe Ia come from long-lived progenitor systems. Unfortunately, there are no good H luminosities available for large samples of galaxies. Since the total luminosity depends on the galaxy distances the supernova rates depend on H_0^2.

Two complementary efforts can be distinguished. One approach is to collect as many supernovae as possible and then define the galaxy sample from which they emerged (Tammann et al. 1994). This is hampered by the fact that galaxies without supernova enter the sample only according to some selection criteria (e.g. contained in a given volume). The other approach is to only include supernovae which have been detected in a pre-defined galaxy sample (Cappellaro et al. 1997). This restricts the number of supernovae significantly. A new approach, which is tailored for more distant searches, is to define a galaxy luminosity function and use this information (as a function of redshift) to determine the rates (Pain et al. 1996, Reiss 1999). This may be the most efficient way to treat this problem avoiding massive redshift surveys which cover all galaxies accessible in the search area and may well require prohibitive amounts of observing time.

Other problems affecting SN rates are the internal extinction in the host galaxy. This extinction depends on the local environment and may differ considerably for the various supernova types. The extinction of course depends on the parent population of the supernovae. SNe Ia presumably originate in an older population where extinction should be less of a problem (but see below and section 3.1 for doubts on the universality of this as-

[4] `http://www.supernovae.net/isn.htm`
[5] `http://www.kusastro.kyoto-u.ac.jp/vsnet/SNe/SNe.html`
[6] `http://www.ggw.org/asras/snimages`

sumption). Unless the age and initial mass function of the supernova parent population is the same as that of the dominant stellar population, the assumption that the B luminosity may be a good comparison is questionable.

The rates of SNe Ia are very low with about 1 event every 500 to 600 years for a galaxy with $10^{10}L_{B_\odot}$ and a Hubble constant of 65 km s^{-1} Mpc^{-1} (Cappellaro et al. 1997, Reiss 1999). There is a dependence on galaxy type which shows that SNe Ia are observed less often in early type (elliptical and S0) galaxies than in spirals. This goes against the claim that they emerge from very old stellar populations. A further puzzling fact questioning the old paradigm is that there seems to be some preference of SNe Ia in star forming galaxies to lie in or near spiral arms (Bartunov et al. 1996) or at least in their vicinity (McMillan & Ciardullo 1996) which would make them of intermediate age (>0.5 Gyr). The rate in the field and in galaxy clusters seems to vary very little (Reiss 1999).

The rates of distant ($z > 0.3$) supernovae have been derived only for two very small samples (Pain et al. 1996, Reiss 1999). For the distant supernovae the difficulties in calculating rates are exacerbated by the small number statistics of spectroscopically classified objects. An additional factor for the distant searches are the exact galaxy luminosities and an approach over some general luminosity functions is required (Reiss 1999). The restriction to a given filter passband (mostly the B band) becomes questionable as there are significant color changes for distant galaxies. It is hence not too surprising that the two estimates are not concordant. Larger supernova samples at high redshift have already been observed and new rates will become available soon.

2.1.2 Light curves

Light curves form one of the main information sources for all supernovae. Typically they are observed in the broad-band optical filters following the Bessell (1990) system, which combines the older Johnson (Johnson & Harris 1954) and Cousins (1980, 1981) filter passbands. The optical *UBVRI* bands have been observed for bright, nearby supernovae. Observations in the near infrared *JHK* filters have been obtained for a few supernovae only (Elias et al. 1981, 1985, Frogel et al. 1987, Meikle 2000).

Figure 1 displays the characteristic shape of SNe Ia in the various filters (Suntzeff et al. 1999, Jha et al. 1999, Hernandez et al. 2000). Observers usually use the B maximum as the zero-point for the light curves. We will follow this practice here as well.

The light curves have been investigated in detail over the last decade. After the early assumption of a single time evolution (Minkowski 1964, Leibundgut 1988, Leibundgut et al. 1991a) clear differences emerged when new objects were observed in more detail. A striking example of the differences has been demonstrated by Suntzeff (1996) with the R and I light curves. Earlier indications of deviant objects had been ignored (Phillips et al. 1987, Frogel et al. 1987, Leibundgut 1988).

The exact, objective description of optical light curves has become an industry (Hamuy et al. 1996d, Riess et al. 1996a, Vacca & Leibundgut 1996, Perlmutter et al. 1997). However, no overall agreement has emerged yet.

Rise Times SNe Ia rise to maximum very fast. Only in very lucky occasions have early observations been recorded. One such case has been the occurrence of a second SN Ia within 100 days in the same galaxy (SN 1980N and SN 1981D - Hamuy et al. 1991). The

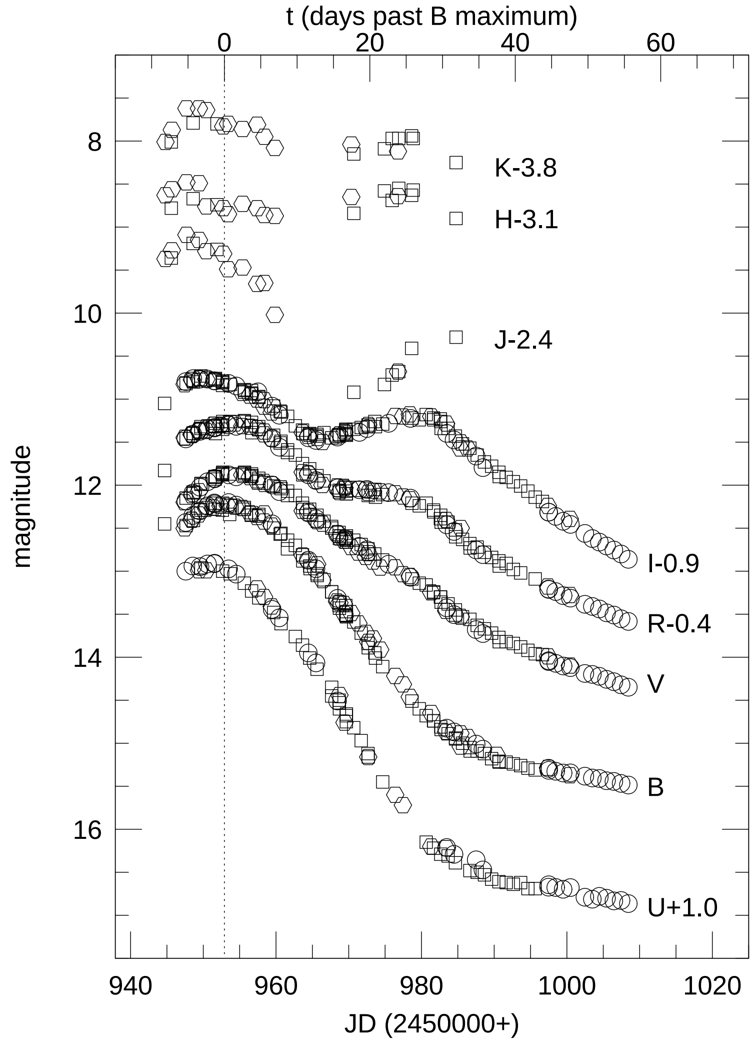

Figure 1: Optical light and near-infrared light curves of SN 1998bu. The symbols are for different data sets (circles: Suntzeff et al. (1999); squares: Jha et al. (1999); hexagons: Hernandez et al. (2000)).

new supernova could be detected on the deep photographic plates obtained to follow the late light curve of the first object. Thus the earliest observations were obtained 15.3 days before B maximum light was reached. Other observations this early were reported for a small number of SNe Ia (SN 1971G: -17 days, Barbon et al. 1973b; SN 1962A: -16 days, Zwicky & Barbon 1967; SN 1979B: -16 days, Barbon et al. 1982; SN 1999cl: -16 days, Krisciunas et al. 2000).

Densely sampled supernova searches provide the best chance to obtain very early observations. The current Lick Observatory Supernova Search has already discovered several objects very early (SN 1994ae; -13 days, Riess et al. 1999a).

A systematic search for early supernova data has been conducted by Riess et al. (1999b). The earliest reported observations are for SN 1990N (-17.9 days) and SN 1998bu (-16.7 days). It is thus clear that SNe Ia rise to B maximum in more than 18 days. The rise is very steep with about half a magnitude per day brightness increase until about 10 days before maximum (SN 1990N; Riess et al. 1999b).

The pre-maximum light curve is often approximated with a t^2 function (Riess et al. 1999b, Aldering et al. 2000) assuming an expanding fireball with a very slowly changing temperature. The fit to the data demonstrates the suitability of such an assumption. Riess et al. find a rise time of about -19.5 days for SNe Ia. The rise time determined by Vacca & Leibundgut (1996) and Contardo et al. (2000) were based on a less extended data set and a different functional form.

Maximum phase The maximum phase starts about 5 days before the peak in the B filter. At this time a SN Ia has most likely reached its maximum brightness in the near-IR filters *JHK* (Meikle 2000). We currently have IR observations for only one SN Ia at these early phases, SN 1998bu (Meikle & Hernandez 1999, Hernandez et al. 2000). A dip in the light curve about 10 days after B maximum had been observed in *JHK* for other SNe Ia (Elias et al. 1985, Meikle 2000). SN 1986G possibly had the IR maxima observed just a few days before the B maximum (Frogel et al. 1987).

Although there is quite a range in relative epochs of maximum in the different filters it is clear that in most cases SNe Ia reach maximum earlier in I than in B (Contardo et al. 2000). The one object which clearly deviates is SN 1991bg. It reached I maximum about 6 days after the B maximum (Contardo et al. 2000). This is in striking contrast with the other object reported to be in a similar class, SN 1997cn, which reached maximum in all filters within a couple of days (Turatto et al. 1998).

The peak phase can be approximated fairly well by Gaussian curves (Vacca & Leibundgut 1996, Contardo et al. 2000, Pinto & Eastman 2000) or second-order polynomials (Hamuy et al. 1996d, Riess et al. 1999a).

The colors evolve very rapidly and non-monotonically around maximum. While they appear fairly constant during the pre-maximum phase, they change from blue ($B-V \approx -0.1$) at 10 days before to red ($B-V \approx 1.1$) 30 days after maximum. Other colors evolve similarly, although not as strongly ($V-R$, $R-I$, Ford et al. 1993). A very strong color evolution can be seen in $J-H$ (from -0.2 to 1.3), while the $H-K$ changes only mildly (from 0.2 to -0.2; Elias et al. 1985, Meikle 2000), the only color where SNe Ia become bluer. In this color the difference between individual supernovae can be substantial (Meikle 2000). At maximum the typical absorption corrected $B-V$ is about -0.07 ± 0.03. The $V-I$ color is -0.32 ± 0.04 with a slight dependence on the light curve shape (Phillips et al. 1999).

After maximum the supernovae start to fade slowly and go into a decline at UV and blue (U and B) wavelengths. The redder wavelengths progressively show a decrease of the decline after about 20 days (V), to a shoulder (R) and a second maximum (*IJHK*). The epoch of the second maximum in I also correlates with other parameters, in particular the decline rate and the peak luminosity (Suntzeff 1996, Hamuy et al. 1996d, Riess et al. 1996a).

Second maximum The characterization of the decline is not easy and several methods have been proposed. Only the densely sampled and accurate photometry which became available in the last decade has allowed us to explore this part of the light curve more systematically.

A pronounced second maximum has been observed in the I and redder light curves (Ford et al. 1993, Suntzeff 1996, Lira et al. 1998, Meikle 2000). This has been a rather unexpected feature but had been pointed out already by Elias et al. (1981, 1985). The second maximum has not been characterized formally and its interpretation is still unclear (see section 4). The I light curve peaks between 21 days (SN 1994D) and 30 days (SN 1994ae) after the B maximum. The peaks, however, with quite some spread, are around 29, 25, and 21 days past B maximum for J, H, and K, respectively. The rise of the second maximum is very pronounced and amounts from dip to maximum to about 0.7 mag in J, 0.6 mag in H, and 0.4 mag in K (Elias et al. 1985, Leibundgut 1988, Meikle 2000). These values are based only on very few objects and any systematic differences could not be described. It is, however, striking to see how well the templates fit new data like SN 1998bu (Meikle 2000).

This second peak has been conspicuously absent in the I light curves of SN 1991bg (Filippenko et al. 1992b, Turatto et al. 1996) and SN 1997cn (Turatto et al. 1998), although a slight change in the B and V light curve decline rates during this phase has been reported (Leibundgut et al. 1993). The IR light curves of SN 1986G (Frogel et al. 1987) display only a plateau instead of a well formed peak.

Late declines After about 50 days the light curves settle onto a steady decline which is exponential in luminosity. The decline rates are the same for basically all SNe between 50 and ∼120 days (Wells et al. 1994, Hamuy et al. 1996d, Lira et al. 1998). The B light curves decline by about 0.014 mag/day, the V by 0.028 mag/day, and I by 0.042 mag/day. Exceptions are SN 1986G (Phillips et al. 1987) and SN 1991bg (Turatto et al. 1996). They declined faster in B (0.019 and 0.020 mag/day, respectively). The decline in V is identical for all SNe Ia. In I SN 1991bg declined marginally slower than other SNe Ia (0.040 mag/day). The IR light curves have been observed for only a handful of objects to about 100 days past maximum (Meikle 2000). The decline rate is fairly constant for the few objects where it has been observed. It is 0.043 mag/day in J and 0.040 mag/day for H and K (Elias et al. 1985, Leibundgut 1988). These values are almost entirely based on SN 1972E, SN 1980N, and SN 1981B. Only SN 1980N, SN 1981B, and SN 1981D have been followed to about 380 days after maximum and show a more or less exponential decline out to the last observation (Elias & Frogel 1983). Data in this range are clearly missing and these epochs will be important to explore in the future.

Not many SNe Ia have been followed much further. At a phase of 150 days past B maximum a typical supernova is about 5 magnitudes below its peak brightness and many have disappeared into the glare of their host galaxy. The few objects which have been observed longer show a change of slope in the V, R, and I filters between 120 and 140 days (Fig. 2; Doggett & Branch 1985, Lira et al. 1998), when the decline slows to 0.014, 0.015, and 0.011, respectively. The decline rates after 140 days are identical for SN 1990N, SN 1992A, and SN 1991T (Suntzeff 1996, Lira et al. 1998). The B light curve maintains its previous slope also at these late phases (Minkowski 1964, Kirshner & Oke 1975, Suntzeff 1996, Lira et al. 1998).

A special case is SN 1991T which was observed out to over 1000 days. A flattening of the B, V, and R light curves after about 600 days was found (Schmidt et al. 1994) and has been observed until 2570 days after maximum so far (Sparks et al. 1999). The flattening can be explained by a light echo produced in a dust layer in front of the supernova.

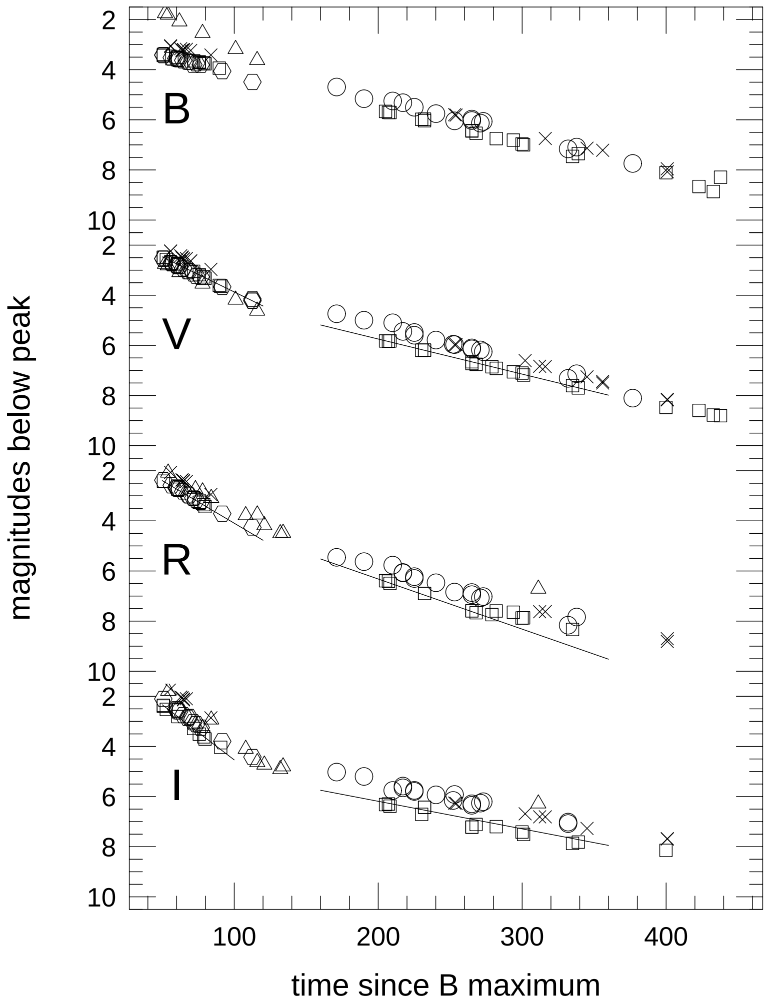

Figure 2: Optical light curves between 100 and 200 days after maximum. Data of the following supernovae are plotted: SN 1992A (squares), SN 1994D (hexagons), SN 1991T (crosses), SN 1990N (circles), SN 1986G (triangles; *V* only), and SN 1989B (triangles; *R* and *I* only). The lines are fits to the data of SN 1992A.

Bolometric light curves Given the complex and wavelength-dependent nature of the opacity in SNe Ia it is clear that the brightness evolution in individual filter bands depends on these modulations. Physically more relevant is the total flux and its change with time. Bolometric light curves can provide exactly this. Of course, we can not construct fully bolometric light curves, but only sum over the observed flux. Since this includes the near-UV, optical and near-infrared wavelengths, such light curves are often referred to as UVOIR. We will refer to these light curves as bolometric in the following. Note that we are explicitly excluding the contributions by $\gamma-$rays. Since most of the flux emerges in the optical, at least during the first few weeks, the construction of bolometric light curves is possible (Suntzeff 1996, Vacca & Leibundgut 1996, Turatto et al. 1996, Contardo et al. 2000).

The contribution from the UV is expected to be less than 10% at maximum (Suntzeff

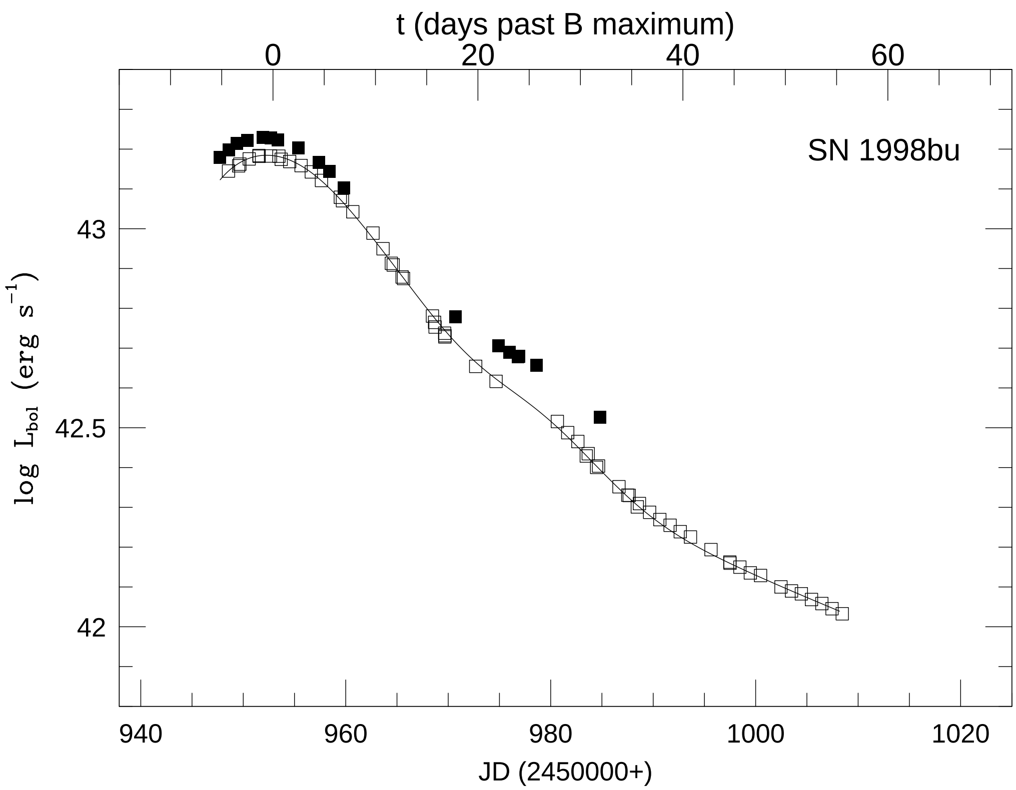

Figure 3: Bolometric light curve of SN 1998bu (Contardo 2000). The open symbols show the *UBVRI* integration while the filled squares display the bolometric light curve including the *JHK* bands. The line is the bolometric light curve derived from fitting the *UBVRI* filter curves individually before integration.

1996, Leibundgut 1996) and the IR should also not contribute significantly. The published bolometric light curves extend from about 10 days before maximum and span a little over 100 days. The most striking feature is the secondary shoulder which shows up between 20 and 40 days past maximum (Suntzeff 1996, Contardo et al. 2000) in all SNe Ia but SN 1991bg. We show here the bolometric light curve of SN 1998bu (Fig. 3; Contardo 2000). The secondary shoulder is visible about 30 days after maximum. The contribution of the near-IR passbands *JHK* is about 5% at peak as predicted and increases through the shoulder as the SN turns redder.

The peak phase of the bolometric light curve is slightly asymmetric with the rise from half the peak luminosity being slightly shorter than the decline to this brightness (Contardo et al. 2000). It takes from 7 to 11 days to double the luminosity before maximum and 10 to 15 days to halve it again. The rise to and fall from the maximum is slower for more luminous objects.

The secondary shoulder is visible in many objects, but may vary considerably in strength and duration. As with the filter passbands, the shoulder is occurring later for more slowly declining supernovae (as measured by the decline to half the luminosity) and hence the more luminous objects (Contardo 2000).

At late phases SNe Ia settle onto a decline which is very similar for all objects, with the exception of SN 1991bg. The decline rate between 50 and 80 days past maximum for the bolometric flux corresponds to 0.026 ± 0.002 mag/day, while SN 1991bg declined 0.030 mag/day at this phase.

2.1.3 Luminosity

One of the most important ingredients for any analysis of the energetics of SNe Ia is the maximum luminosity. It is also essential for the use of SNe Ia as distance indicators and the measurement of the Hubble constant (Branch & Tammann 1992, Branch 1998 and references therein). The best values are currently derived for the few nearby SNe Ia for which a distance can be determined by Cepheids. A mean value of $M_B = -19.5 \pm 0.1$ and $M_V = -19.5 \pm 0.1$ (error of the mean) for a set of 8 SNe Ia has been measured (Saha et al. 1999, Gibson et al. 2000). It has become custom to normalize all SNe Ia luminosities to a given decline rate (see section 3.1). Hence, slightly different averages can be found for analyses which make differing assumptions on absorption and perform such a normalization. A subset of five supernovae treated differently for absorption yields $M_B = -19.7 \pm 0.1$, $M_V = -19.6 \pm 0.1$ and $M_I = -19.3 \pm 0.1$ (Suntzeff et al. 1999), while another collaboration (Jha et al. 1999) found $M_V = -19.3 \pm 0.2$ after the decline rate correction, which amounts to $\Delta m_{corr} = -0.26$ globally, for four SNe Ia. The Suntzeff et al. and Jha et al. absolute magnitudes are hence the same and differ only marginally from the uncorrected values given in Saha et al. The discrepancy can be traced to the absorption corrections. Suntzeff et al. and Jha et al. apply a correction for the host galaxy absorption which is not done explicitly in Saha et al.

Apart from the systematic differences on the exact absolute value of the luminosity it is striking how small the overall scatter of the measurements is even before the light curve shape corrections are applied. The total range spans less than 0.5 magnitude in B and V (Saha et al. 1999, Gibson et al. 2000). It has to be noted that no Cepheid distance to a truly peculiar object, e.g. SN 1991bg or SN 1991T, has been measured so far. The data for NGC 4639 (SN 1991T) have been obtained and are being analyzed.

The bolometric luminosity of SNe Ia has been measured for only a handful of objects. The typical maximum luminosity these objects reach (see Table 1) is 10^{43} erg s^{-1} (Contardo et al. 2000). Faint events, like SN 1991bg, are, however, much less luminous ($\sim 2 \times 10^{42}$ erg s^{-1}), while the brightest objects reach $> 2 \times 10^{43}$ erg s^{-1} (SN 1991T).

2.1.4 Spectra

For a recent, very complete, review on the optical spectra of supernovae of all types see Filippenko (1997a). SNe Ia are discussed extensively and readers are referred to this publication for optical spectra (and references). A large sample of infrared spectra is described in Meikle et al. (1996) and Bowers et al. (1997).

The evolution of a SN Ia spectrum is dominated by the changing influence of various emission and absorption lines. During the early phases until the late decline in the light curve begins the spectrum is dominated by P-Cygni lines of intermediate-mass elements. Most prominent is the Si II doublet ($\lambda\lambda$6347Å and 6371Å) with a prominent absorption of its P-Cygni profile around 6100Å and for a long time the defining feature of SNe Ia. Other prominent lines of SNe Ia near maximum light are Ca II ($\lambda\lambda$3934Å, 3968Å, and λ8579Å), Si II (λ3858Å, λ4130Å, λ5051Å, and λ5972Å), Mg II (λ4481Å), S II (λ5468Å and $\lambda\lambda$5612Å, 5654Å), and O I (λ7773Å). The spectrum is scattered with low-ionization Ni, Fe, and Co lines which increase after the peak (e.g. Jeffery et al. 1992, Mazzali et al. 1993, 1995, 1997). Typical velocities observed in the lines are between 10000 and 15000 km s^{-1}.

The spectrum below 3500Å is strongly suppressed by lines from iron-peak elements (Harkness 1991, Pauldrach et al. 1996). UV spectra have been obtained for only a few SNe Ia and only SN 1990N (Leibundgut et al. 1991b) and SN 1992A (Kirshner et al. 1993) have regular coverage. All IUE observations are available as a uniform sample (Cappellaro et al. 1995). The features in this part of the spectrum are not due to regular line formation, but are regions of suppressed line opacity (Pinto & Eastman 2000, see also section 4.2).

The near-IR spectral range is comparatively featureless. Lines of Si II ($\lambda 1.67\mu$m), Ca II ($\lambda 1.15\mu$m), Mg II ($\lambda 1.05\mu$m) and iron-peak elements (between $1.5\mu\text{m}<\lambda<1.7\mu$m and $2.2\mu\text{m}<\lambda<2.6\mu$m) are observed (Wheeler et al. 1998). A debate on the possible identification of He I ($\lambda 1.083\mu$m) started with the observations of SN 1994D (Meikle et al. 1996, Mazzali & Lucy 1998).

There is no appreciable polarization measured in broad-band photometry and spectra of SNe Ia (McCall et al. 1984, Spyromilio & Bailey 1993, Wang et al. 1996, 1997). With the exception of SN 1996X (Wang et al. 1997) polarized at about 0.2%, all SNe Ia have no detectable polarization in their spectra (Wang et al. 2000).

After the transition from an absorption spectrum, which is superposed on a pseudo-continuum, to a pure emission spectrum all lines can be attributed to forbidden Co and Fe transitions (Kirshner & Oke 1975, Spyromilio et al. 1992, Kuchner et al. 1994, Bowers et al. 1997, Mazzali et al. 1998, Wheeler et al. 1998). The nebular phase is dominated by the changing strength of these individual line multiplets.

Deviations Some SNe Ia have shown significant deviations from the above picture. Especially SN 1991T (Filippenko et al. 1992a, Phillips et al. 1992, Jeffery et al. 1992, Mazzali et al. 1995) and SN 1991bg (Filippenko et al. 1992b, Leibundgut et al. 1993, Turatto et al. 1996, Mazzali et al. 1997) have drawn attention to individual differences among SNe Ia.

SN 1991T developed the classic Si II and Ca II lines very late and also with diminished strength. Instead, its early spectrum was dominated by Fe III lines (Filippenko et al. 1992a, Ruiz-Lapuente et al. 1992). In the nebular phase SN 1991T was very similar to other SNe Ia (Leibundgut et al. 1993) suggesting similar excitation conditions and densities. The line widths did, however, indicate a higher expansion velocity (Spyromilio et al. 1992, Mazzali et al. 1998).

SN 1991bg on the other hand displayed an absorption trough near $\approx$4000Å which was attributed to Ti II ($\lambda\lambda$4395Å, 4444Å, and 4468Å) absorption (Filippenko et al. 1992b, Mazzali et al. 1997). The emergence of this line blend has been explained as a temperature effect (Nugent et al. 1995).

The stronger lines all show a clear velocity evolution with epoch, which differs significantly among individual supernovae (e.g. Branch et al. 1988, Leibundgut et al. 1993, Nugent et al. 1995, Patat et al. 1996). These measurements are not very reliable as they assume that the expansion velocity can be determined from the absorption trough of the P-Cygni line. Typical lines analyzed are the Si II and the Ca II doublets. High velocity carbon has been inferred from the earliest spectrum of SN 1990N blended with the Si II doublet (Fisher et al. 1997). The identification is based on the line profile, with the C II (λ6580Å) line formed in a detached shell. It is unclear, whether this is a regular feature of other SNe Ia as well or was special to SN 1990N.

Line strengths change among individual SNe Ia as well (Nugent et al. 1995). In particular, a range of Ca II and Si II line strengths has been found. At late phases the line widths also show differences (Mazzali et al. 1998).

2.2 Other wavelengths

There have been attempts to detect nearby SNe Ia in γ–rays with CGRO. These observations would measure the $\gamma-$rays from the nuclear decay. The COMPTEL observations of SN 1991T have yielded a possible detection (Morris et al. 1997, Diehl & Timmes 1998). Deep observations of SN 1998bu with CGRO have been obtained, but the first reports are negative. The COMPTEL upper limit clearly excludes the most luminous detonation models (Georgii et al. 2000). Also the next γ–ray observatory, INTEGRAL will only detect SNe Ia closer than about 10 to 15 Mpc depending on the explosion models (Timmes & Woosley 1997, Höflich et al. 1998a). Prospects for a direct calibration of he ^{56}Ni mass hinge on chances for very nearby events.

No X–ray observations have been reported for SNe Ia. These supernovae are not expected to emit any significant radiation in this wavelength regime.

Radio observations of SNe Ia have been obtained, but no positive detection has been reported (Weiler et al. 1989, Eck et al. 1995). A total of 24 SNe Ia, including all nearby and bright objects, has been observed at radio wavelengths without a single detection (Panagia et al. 1999).

3 Deductions

This section concentrates on derivatives from the observations and their possible interpretations. Recent years have seen several variations emerging from the formerly very uniform picture. The original assertion that all SNe Ia are the same had to be abandoned as better data became available. In particular, the strong belief in the standard candle picture, so important for the cosmological applications of SNe Ia, has been overthrown by large deviations in light curve shape and spectral appearance. The monolithic picture of SNe Ia has been replaced by several correlations of observable parameters. The full extent of these correlations has not yet been explored and new ones are still uncovered.

One of the key questions will be whether SN 1991bg represents an extreme case in the SN Ia picture or whether it should be considered separate and independent of the majority of Ia events. Specifically, it would be interesting to see whether this object underwent a fundamentally different explosion (maybe still in the realm of the thermonuclear explosions) or whether it represents a stripped version of the regular explosions.

3.1 Correlations

Despite their differences SNe Ia seem to follow a few invariants in their appearance. The best-known is the linear decline-rate *vs.* luminosity correlation (Phillips 1993). There are now several implementations of this correction: the template fitting or Δm_{15} method (Hamuy et al. 1996b, Phillips et al. 1999), the multi-light curve shape correction (Riess et al. 1996a, 1998a), and the stretch factor (Perlmutter et al. 1997). Earlier versions of such light curve shape *vs.* luminosity relations had been proposed (Barbon et al. 1973a, Pskovskii 1977, 1984), but could not be supported by the available data.

The decline rate correction methods are entirely empirical. They rely on the fact that the fit around the Hubble line in the Hubble diagram improves when they are applied. Originally based on a set of supernovae with known relative distances a linear relation for the decline in the B light curves and the B, V, and I filter luminosities was determined (Phillips 1993). It has to be stressed that the relation is normally defined for the decline in the B filter light curve. The coefficients of this relation have changed significantly over the last few years as the distances and extinction corrections have been refined (Hamuy et al. 1996c, Phillips et al. 1999; Riess et al. 1996a, 1998a). Higher order fits have now been proposed (Riess et al. 1998a, Phillips et al. 1999, Saha et al. 1999). The stretch factor method describes the light curves by a simple stretch in time. A basic template light curve is used and then stretched to match the observations (Perlmutter et al. 1997). This method only works for the B and V light curves through the peak phase, but breaks down about 4 weeks after peak. It is clear from the R and I light curve shapes that such a stretching procedure can not work linearly for all filters. Another potential problem with this method is that it predicts the relative times between filter maxima to stretch as well, which is not observed. Within these limitations it has been shown that the stretching provides similar corrections as the other methods discussed above (Perlmutter et al. 1997; but see below).

Although some of the methods are equivalent they do not reproduce too well. An example is given in Figure 4 (top) which shows the magnitude corrections determined by the three methods for the same supernovae. For the construction of this diagram we have calculated the magnitude correction given in Phillips et al. (1999) for the template method. The values for MLCS have been taken from Table 10 in Riess et al. (1998a) and the stretch correction derived from Table 2 in Perlmutter et al. (1999). Note that the assumptions for these magnitude corrections are not identical for all methods. While Phillips et al. (1999) used BVI light curves for their corrections, the ones by Riess et al. (1998a) and Perlmutter et al. (1999) are based on B and V only. A significant scatter is noticeable. There is also a significant zero-point offset of 0.25 ± 0.04 magnitudes for the MLCS method, while the stretch yields only a marginal offset of -0.03 ± 0.01 mag. The slopes are further 0.77 ± 0.13 and 0.29 ± 0.04 for MLCS and stretch, respectively. These are significantly different from the one expected, if the methods were identical. The scatter is considerable and also a concern. A similar conclusion can be drawn from the comparison of the estimated absorption towards the supernovae (Fig. 4 bottom). The data are from the same sources as the magnitude corrections. In particular, the large spread of absorptions from the template method compared to both MLCS and stretch determinations (which are based on B and V only for these data here) is striking. An overall offset is apparent here as well. These are all signatures of subtle, but significant differences in the treatment of

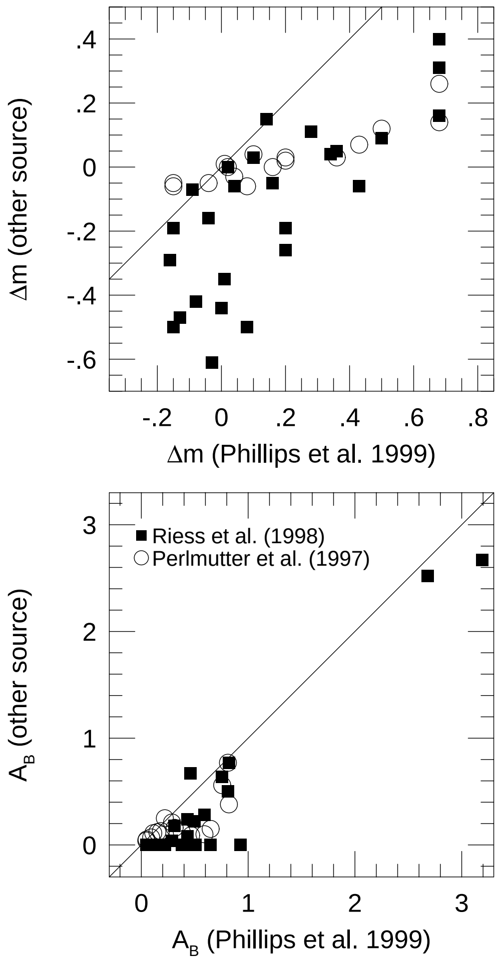

Figure 4: Comparison of the light curve parameters from different methods. The multi light curve shape (Riess et al. 1998a) and the stretch corrections (Perlmutter et al. 1997) are compared to the template (Δm_{15}) method for the sample of nearby supernovae. The top diagram shows the magnitude corrections based on the light curve shape and the bottom graph displays the inferred absorption for the different methods.

the data. A similar conclusion has been drawn in connection with data for distant SNe Ia (Drell et al. 1999), but attributed to evolution.

The main differences are related to the exact correction for dust in the host galaxy. The determination of the extinction relies on the availability of an independent absorption indicator. In fact, the reddening law in most cases has to be assumed instead of being derived (for exceptions see Riess et al. 1996b who find a slight deviation from the Galactic reddening law and Phillips et al. (1999) who don't). The best that could be done in the past was to assume that SNe Ia all have the same (Branch & Tammann 1992 and discussion therein) or a well-defined color (Riess et al. 1996a) at maximum. With this assumption and the application of the Galactic reddening law, absorptions could be measured. Phillips et al. (1999) recently proposed to use the color at the transition to the nebular phase at an epoch of about 30 days past peak rather than the color at maximum. At the transition all supernovae are at about the same epoch since explosion and the various iron-element emission lines, which dominate the spectrum, have the same relative strengths. The peak colors depend on the exact changes of the optical depth in the ejecta. The color evolution at maximum is also very rapid and small measurement errors can result in systematically wrong reddening estimates.

An attempt has been made to combine the known relations into a method for distance determinations from minimal observations (Riess et al. 1998b). With a single spectrum during the peak phase and photometry at one epoch in at least two filters the absolute luminosity and the peak brightness of the event can be determined. The spectrum in this case provides the information of the phase/age of the supernova and, through the line strengths, the 'luminosity class,' while the reddening and brightness are determined from the photometry. The assumption in all this is, of course, that all SNe Ia can be described in a single parameter family and the reddening law is well understood.

An independent fitting method has been applied by Vacca & Leibundgut (1996, 1997) and Contardo et al. (2000). Here the data are approximated with a function which depends on a number of parameters. This fitting method also reproduces the decline rates found by other methods (Vacca & Leibundgut 1997). Its application to larger data sets is still missing, but would provide a strong independent check on the relations.

There are other parameters which correlate with the peak luminosity of SNe Ia. They are the rise time to maximum (Riess et al. 1999b), color near maximum light (Riess et al. 1996a, Tripp 1998, Phillips et al. 1999), line strengths of Ca and Si absorption lines (Nugent et al. 1995, Riess et al. 1998b), the velocities as measured in Fe lines at late phases (Mazzali et al. 1998), the host galaxy morphology (Filippenko 1989, Hamuy et al. 1996a, Schmidt et al. 1998), and host galaxy colors (Hamuy et al. 1995, Branch et al. 1996). There may be indications that the secondary peak in the I light curves and also the shoulder in the bolometric light curves correlate with the absolute luminosity (Hamuy et al. 1996d, Riess et al. 1999a, Contardo et al. 2000).

3.2 Energetics

The observable emission of SNe Ia is powered completely by the decay of radioactive ^{56}Ni and its radioactive daughter nucleus (Colgate & McKee 1969, Clayton 1974). ^{56}Ni is synthesized in the explosion and decays by electron capture with a half-life of 6.1 days to ^{56}Co. The cobalt decays through electron capture (81%) and β^+ decay (19%) to stable ^{56}Fe with a half-life of 77 days. The early phase is dominated by the down-scattering and the release of photons generated as $\gamma-$rays in the decays (Höflich et al. 1996, Eastman 1997, Pinto & Eastman 2000). The dominating opacity comes from the strongly velocity broadened lines and the incoherent scattering ('line splitting').

At late phases the optical radiation is escaping freely and the ejecta are cooling through emission lines. The $\gamma-$ray escape fraction increases continually and less and less energy is converted to optical photons (Leibundgut & Pinto 1992). After about 150 days the contribution from positrons becomes significant (Axelrod 1980, Milne et al. 1999). These positrons are from a minor channel of the ^{56}Co decay and annihilate in the ejecta after losing their kinetic energy in elastic scatterings (Axelrod 1980, Leibundgut & Pinto 1992, Ruiz-Lapuente et al. 1995b, Milne et al. 1999). So far it had been assumed that all the energy from the positron decay would be deposited in the ejecta, but recent studies indicate that depending on the magnetic field structure in the ejecta some positrons could escape and the decay energy is lost for the supernova (Colgate et al. 1980, Ruiz-Lapuente & Spruit 1998, Milne et al. 1999).

After several hundred days the emission should change dramatically when the ejecta has cooled down far enough that the bulk of the cooling occurs through far-infrared fine structure lines of iron (Fransson et al. 1996). This has so far not been observed in any SN Ia as they are too faint at this point. In some cases the emission becomes dominated by light echos (e.g. 1991T: Schmidt et al. 1994, Boffi et al. 1999).

3.3 Progenitors

All inference of the progenitor systems of supernovae has to come from the explosion observations themselves. The name of the game is to match stellar evolution models with some parameters indirectly derived from the explosions. Excellent reviews of this topic are available (Branch et al. 1995, Renzini 1996, Livio 1999, Nomoto 1999) and we refer the reader to the references in these compilations.

The observations of SNe Ia tell us that they emerge from a compact object as is inferred from the light curves, i.e. the short duration of the peak phase. The fast decline and the large leakage of $\gamma-$rays, although only measured indirectly, imply a small mass of the ejecta as well. Note that this statement implicitly made use of the thermonuclear explosion models (cf. Section 4). The glaring absence of the most abundant elements in the universe, hydrogen and helium, narrow the selection down to a few highly evolved objects. Also the appearance in elliptical galaxies with their old stellar population hints at significant nuclear processing before explosion. Indirectly these observational results indicate that SNe Ia do not emerge from single star systems. The absence of hydrogen and helium must mean that the star has removed its envelope. The longevity of the progenitors, at least for SNe Ia in elliptical galaxies, and the trigger of the explosion also point to binary systems.

An important piece of information is the rarefied environment in which SNe Ia explode. Radio emission is the telltale signature of such circumstellar material, but has not been detected in a single SN Ia. This also sets limits on mass-loss from companion stars. A potentially powerful analysis tool would be the detection of narrow Hα or He emission from gas shed by the companion star. The best observations to test for such emission have been obtained for SN 1994D without a detection (Cumming et al. 1996). The investigation of local interstellar environments of SNe Ia has so far been inconclusive (Van Dyk et al. 1999), but there are at least four cases which could lie close or within an area of active star formation.

The rareness of SNe Ia is a further indicator of a special stellar evolution scenario leading to these explosions. With so few stars producing SNe Ia the selection criterion must be rather severe.

The uniform appearance is often used as an argument for a restrictive progenitor base, but in the light of the recent observations, in particular of the faint objects SN 1991bg and SN 1997cn, this should be investigated again carefully. On the other hand, the strong correlations hint at fairly unique progenitor systems allowing for some variations.

Most discussions on SN Ia progenitors try to answer two questions. At what mass does the white dwarf explode (Chandrasekhar or sub-Chandrasekhar) and what is the donor star. The first question should be answerable with exact determinations of the Ni masses (see § 3.4) and the combination of this energy source with the ejecta energy which can be measured from late-phase line widths (e.g. Mazzali et al. 1998). With the velocities and the column density to $\gamma-$rays it should be possible to estimate a total ejecta mass. So far, we have not been able to derive reliable ejecta masses at all.

The binary companion to the white dwarf could be either another white dwarf ('double-degenerate'), in which case the two would merge due to orbital energy loss by gravitational radiation, or a regular 'live' star which could be either in its giant or main-sequence phase (Renzini 1996). In the second case that star transfers either hydrogen or helium to the white dwarf which burns the material in a steady phase at its surface. Such systems are well known as cataclysmic variables and novae (in the case of a main-sequence companion) or symbiotic stars (where the companion is a red giant). Supersoft X-ray sources have been identified as white dwarfs with steady burning hydrogen shells (see Kahabka & van den Heuvel 1997 for a recent review). Their potential as progenitors of SNe Ia depends on the effectiveness with which the white dwarf can increase its mass towards the Chandrasekhar mass (Hachisu et al. 1999a, b) or whether sub-Chandrasekhar explosions are possible (Renzini 1996). Whether SNe Ia in elliptical galaxies can be explained by such systems is controversial. The critical parameter is the mass of the companion star. To reach ages of $\sim 10\times10^9$ years the companion can not be more than 0.9 to 1.0 $M_\odot$ (Hachisu et al. 1999). For compact binary supersoft sources the companion mass has to be larger than 1.2 $M_\odot$ which would make them too short-lived for progenitors in elliptical galaxies (Kahabka & van den Heuvel 1997).

The double degenerate progenitor models have rebounded in recent years with the detections of several systems with a life time short enough (Maxted & Marsh 1999). One system with a total mass near the Chandrasekhar limit has been found (Koen et al. 1998). Earlier searches for such binaries had been unsuccessful (e.g. Bragaglia et al. 1990, Renzini 1996). There are several questions connected to such progenitor scenarios as well. Especially the evolutionary path through two common-envelope phases is still very uncertain. Detailed calculations on the final merger are also so far inconclusive and in some cases a collapse to a neutron star is favored (Saio & Nomoto 1998, Livio 1999). Another outcome of such mergers would be super-Chandrasekhar explosions. It has been claimed that SN 1991T with its large Ni mass could be explained this way (Fisher et al. 1999).

Another possible way to investigate progenitor systems is to determine the supernova rate as a function of redshift (Ruiz-Lapuente et al. 1995a, Madau et al. 1998, Yungelson & Livio 1998, Ruiz-Lapuente & Canal 1998, Dahlén & Fransson 1999). The average age of the underlying stellar population will influence the number of progenitor systems available at any given epoch. It is obvious that these rates also depend on the cosmological model, the star formation history, and other observational effects, like dust obscuration (Yungelson & Livio 1999) or inhibition of supernova explosions (Kobayashi et al. 1998). There are no indications of changes of the SN Ia rate out to redshifts of 0.5 reported (Reiss 1999), but the data sets are still very limited.

Note, however, that we do not have to peer deep into the universe to determine differences in SN rates from different progenitor populations. The age differences can be worked out in the local neighborhood by comparing the rates in galaxies of different morphological types. Such a prediction from the evolutionary models would be very helpful to explain the comparatively large rate in spiral galaxies (Cappellaro et al. 1997).

Of course, any difference between SNe Ia at large look back times and in the local neighborhood would indicate differences in the progenitors. No large differences have been detected so far (cf. Section 2). Recent discussions on changes in rise times (Riess et al. 1999c, Aldering et al. 2000) and possible color evolutions will have to be followed closely in this respect.

Without clearer indications from observations the progenitor question will remain unanswered. Searches will have to concentrate on left overs in any of the progenitor scenarios. In the case of the hydrogen transfer from the companion a thin layer of hydrogen should still be on the surface of the explosion or in the wind of the companion. It could possibly be observed as a narrow line. The double-degenerate case would produce a significant mass range and possibly also asymmetric explosions depending on the accretion of the companion.

3.4 Nickel masses

Once we are in the situation where we can measure the amount of nickel produced in the explosion, we will probe the explosion mechanisms more directly. Since most of the white dwarf is burned to the radioactive ^{56}Ni and we are observing the subsequent energy release, we are probing the most sensitive part of the explosion.

Observationally the measurement of the nickel mass has become possible recently with the advent of larger telescopes and the development of better radiation diagnostics. There are two main routes to nickel masses in SNe Ia. One is through the observations of the ashes, i.e. the left over iron from the decays, in the near-infrared and the other by obtaining the total luminosity at peak and the application of "Arnett's law" (Arnett 1982, Arnett et al. 1985, Branch 1992), which states that the energy released on the surface at maximum light is equal to the energy injected by nuclear decays at the bottom of the ejecta. The reason for this is that the atmosphere is turning optically thin (Pinto & Eastman 2000). It is possible that Arnett's law is not exact and the ratio of energy release and input is not exactly unity, e.g. due to asymmetries or multi-dimensional effects. However, is has to be expected that all supernovae show a fairly uniform behaviour and the systematic differences are likely to be small compared with the uncertainties which arise from extinction and the lack of accurate distances.

The bolometric luminosity has been determined only for very few objects (Vacca & Leibundgut 1996, Turatto et al. 1996, Contardo et al. 2000). Since the total luminosity observed at maximum equals the instantaneous radioactive decay energy one simply calculates the amount of nickel and its daughter product, cobalt, at this moment. The time between explosion and maximum is an input parameter in this calculation, although it does not introduce severe uncertainties (Contardo et al. 2000). The assumed distances and reddening are the critical parameters in all these analyses. They are needed for the conversion of the observed flux to absolute units. We have listed in Table 1 the nickel masses as derived by Contardo et al. (2000).

A third possibility is to calculate an exact energy conversion from the decays and compare this against the observed late light curves. The latter approach is complicated by the dependence on the exact models and carries large uncertainties due to partially unknown influences from the positron channel in the decay (Axelrod 1980, Cappellaro et al. 1998, Milne et al. 1999).

Table 1: Absolute B magnitudes and bolometric luminosities. The nickel mass is derived from the luminosity for a rise time of 17 days to the bolometric peak.

SN	(m-M) (mag)	A_B (mag)	$\log L_{bol}$ (erg s^{-1})	$M_{\rm Ni}$ ($M_\odot$)	$t_{+1/2}$ (days)
SN 1989B	30.22	1.55	43.06	0.57	12.9
SN 1991T	31.07	0.67	43.36	1.14	14.2
SN 1991bg	31.26	0.29	42.32	0.10	8.9
SN 1992A	31.34	0.07	42.88	0.37	10.6
SN 1992bc	34.82	0.09	43.22	0.84	13.2
SN 1992bo	34.63	0.11	42.91	0.41	9.9
SN 1994D	30.68	0.09	42.91	0.41	10.4
SN 1994ae	31.86	0.63	43.04	0.55	12.9
SN 1995D	32.71	0.41	43.19	0.77	12.9
SN 1998bu	30.37	1.48	43.18	0.77	13.1

Nickel masses have been derived mostly through the near-infrared observations of [Fe II] and [Co II] lines (Spyromilio et al. 1992, Bowers et al. 1997). These lines have the advantage that they are largely single transitions of low excitation stages and not blended, which is not the case in optical spectra (Axelrod 1980, Kuchner et al. 1994, Mazzali et al. 1998). The low ionization is a further advantage as the atomic data are more reliable than for the higher ionization lines. Critical for this method is the accuracy with which the collision strengths of the lines are known. The uncertainties, especially for the [Co II] and [Co III] lines, are still substantial.

The determinations of the nickel masses are fairly consistent between the different approaches (Contardo et al. 2000). The major uncertainties are the distances to the supernovae, which directly influences the luminosities, both for the lines as well as the bolometric flux.

4 Theory

The detailed theoretical understanding of Type Ia Supernovae is still limited. Two very complicated physical processes are at work in SNe Ia explosions. First there is the explosion mechanism itself, which is still debated and several possibilities are proposed and then there is the complicated, highly non-thermal process of the radiation escape which leads to the observed phenomenon. A recent review of SN Ia theory is presented by Hillebrandt & Niemeyer (2000).

4.1 Explosion models

In general it is agreed that SNe Ia are the result of thermonuclear explosions in compact stars. White dwarfs are favored by their intrinsic instability at the Chandrasekhar mass and the fuel they provide in carbon and oxygen. All the arguments for this scenario have been already clearly laid out before 1986 (Woosley & Weaver 1986 and references therein). Other fuels could be imagined, but all of them have some problems. They either do not provide enough (explosive) energy (like hydrogen) or can not synthesize the intermediate-mass elements (like helium, which detonates). Higher elements are in principle possible, but it is well known that O-Ne-Mg white dwarfs would rather collapse to a neutron star than explode because of the large electron capture effects (e.g. Nomoto & Kondo 1991, Gutiérrez et al. 1996). The initiation of the burning in the degenerate star is, however, a puzzle. For many years it was clear that a detonation (supersonic burning front) would lead to an overabundance of iron-group elements and not enough of the intermediate-mass elements observed in the spectral evolution during the peak phase. A deflagration (subsonic burning) seemed more appropriate, but it was not clear how to prevent the explosions to turn into a detonation. The phenomenological model W7 (Nomoto et al. 1984, Thielemann et al. 1986) or similar explosions (Woosley & Weaver 1986, 1994b) enjoy a great popularity as the explosive input model for spectral calculations since they seemed to reproduce the element distribution fairly accurately (e.g. Harkness 1991, Jeffery et al. 1992, Mazzali et al. 1993, 1995, 1997, Yamaoka et al. 1992, Shigeyama et al. 1992). The burning speed in this model has, however, never been understood in physical terms. Possible alternatives are the pre-expansion of the white dwarf to lift the degeneracy by a slow deflagration first and have the detonation start later (Khokhlov 1991). The critical parameters in these models are the density at the transition from deflagration to detonation, the pre-explosion density, the chemical composition (mostly C/O ratio), and the deflagration speed at the beginning of the burning. The transition density has been proposed as the critical parameter for the nucleosynthesis and hence the amount of Ni produced in the explosion. These delayed-detonation models can reproduce some of the observations (Höflich 1995, Höflich & Khokhlov 1996, Höflich et al. 1996). However, their consistency has been questioned recently (Niemeyer 1999, Lisewski et al. 1999a, b). Another possibility is that the first explosion in the center fizzles and as the star contracts again, the density and temperatures rise high enough to re-ignite carbon near the center and lead to the explosion (Arnett & Livne 1994a, b, Höflich et al. 1995). There are hence several theoretical possibilities to ignite the white dwarf, but it is still not clear which ones are realized in nature. With the variety of SN Ia events observed now, it is possible that SNe Ia come from different burning processes. However, the observed correlations must then be valid across different explosion mechanisms.

Once the explosion has started, the flame has to continue burning enough material to unbind the star. In many calculations this has not occurred and the flame has fizzled. Only recently have some three-dimensional calculations led to weak explosions (Khokhlov 1995, Niemeyer et al. 1996, Reineke et al. 1999).

An altogether different explosion mechanism on sub-Chandrasekhar mass white dwarfs has been explored (Nomoto 1982, Livne 1990, Livne & Glasner 1991, Woosley & Weaver 1994a, Livne & Arnett 1995). In this model, the explosion is generated at the surface of the white dwarf due to a detonation of He at the bottom of the accretion layer. This model solved the progenitor problem by allowing explosions well below the Chandrasekhar mass near the peak of the white dwarf mass distribution. Difficulties here are the initiation of the explosion and the subsequent ignition of the whole star by a pressure wave. Many of these calculations are still parametric and the details have to be worked out (cf. Woosley 1997).

It is customary nowadays to explore several of these explosion models to explain the observations (e.g. Leibundgut & Pinto 1992, Höflich et al. 1995, Höflich & Khokhlov 1996, Höflich et al. 1996).

4.2 Radiation transport

Another complicated process stands between the explosion models and the observations. The release of the photons from the explosion is computationally extremely difficult to follow. The reasons are the continuous change of the energy deposition and the detailed physics of the conversion of the $\gamma-$rays injected inside the ejecta from the radioactive decays to the low-energy photons observed. The opacity changes due to the thinning of the expanding ejecta for the high-energy input, but at the same time the high velocities and the abundance of higher elements with their large number of transitions complicates the calculations (Harkness 1991, Höflich et al. 1993, Eastman 1997, Pinto & Eastman 2000). The exact treatment is still debated, but it has become increasingly clear that the old assumption of a thermal input spectrum is not tenable. Even though SNe Ia display a nearly thermal 'continuum' during their peak phase, they are really dominated by the time-dependent photon distribution. The clearest demonstrations of this fact are the lack of photons in the *J*-band (Spyromilio et al. 1994, Meikle 2000) which is due to the absence of emission lines in this wavelength region and the occurrence of the maximum in different optical filters, which is reversed for most supernovae, i.e. the near-IR filter curves peak before the optical ones (Contardo et al. 2000, Hernandez et al. 2000).

Due to the large opacities in the ejecta the photon degradation proceeds through several channels (e.g. Lucy 1999, Pinto & Eastman 2000). Since the UV region is blocked by many velocity-broadened iron-group lines (Harkness 1991, Kirshner et al. 1993), the photons are progressively redshifted until the optical depth is small enough for them to escape. This occurs first in the near-IR and hence the peak is reached earlier at these wavelengths (Meikle 2000, Contardo et al. 2000). However, only in wavelength regions where plenty of line transitions in the outer layers are available is there any significant flux.

Nevertheless, the optical spectrum has been modeled rather successfully even with thermal input sources (Harkness 1991, Jeffery et al. 1992, Mazzali et al. 1993, 1995, 1997, Nugent et al. 1997). This is possible since the outer layers already encounter a pseudo-thermal input spectrum (Pinto & Eastman 2000). Detailed treatment of the NLTE effects has been included by several groups (Baron et al. 1996, Pauldrach et al. 1996, Höflich 1995, Höflich et al. 1996, Lucy 1999, Pinto & Eastman 2000).

At late phases the ejecta are optically thin for optical and infrared photons and we see a spectrum dominated by collisionally excited Fe and Co lines (Axelrod 1980, Ruiz-Lapuente & Lucy 1992, Spyromilio et al. 1992, Kuchner et al. 1995, Bowers et al. 1997, Mazzali et al. 1998). At these epochs it has been assumed that the energy of the positrons in the ^{56}Co decay is locally deposited. This has recently been questioned because of the increased slope of the light curves (Ruiz-Lapuente & Spruit 1998, Cappellaro et al. 1998, Milne et al. 1999). After about 450 days a thermal instability develops in the ejecta which rapidly cool down from about 3000 K to 300 K. Excitation of optical and near-infrared transitions declines rapidly and the cooling continues by fine-structure lines of Fe in the mid- and far-infrared. This is often referred to as the IR catastrophe. The predictions are that this would happen after about 500 days (Fransson et al. 1996) but it has never been observed so far.

It will take a few more years until these problems can be addressed completely. A closer link between the observations and the models has been pursued by trying to understand the correlations which have been observed. The light curve decline has been modeled (Höflich et al. 1996) and explained as due to differences in the amount of Ni produced in the explosion. Also the color dependence could possibly be explained this way. Other issues like the rise time or the occurrence of the secondary peak in the near-IR remain, however, open. A possible interpretation of the light curve stretching during the peak phase and for the bolometric light curves links the time scales of the Ni decay, the diffusion time (for a constant opacity) and the age of the supernova (Arnett 1982, Arnett 1999).

By comparing the kinetic energy as derived from line widths and the measured Ni masses it should be possible to derive global parameters of the explosion. First such steps have been made by Mazzali et al. (1998), Cappellaro et al. (1998), and Contardo et al. (2000). This alternative route will not replace the detailed modeling of light curves and spectra, but may provide a more direct input for the explosion models.

5 Discussion

Although we can foresee a time when there will be more SNe Ia at redshifts above 0.3 than nearby ones, we will have to learn from the nearby samples with their superior data coverage and quality. The distant supernovae are still observed rather sparsely and lack the wavelength and spectral coverage we can obtain for local events.

The capabilities for detailed supernova studies have increased continuously over the past decade and detailed spectroscopic and photometric data sets will become available at a rapid rate. This will allow us to address very specific questions and focus on model predictions. However, simple model predictions have been lacking so far and the complications in the explosion models and the radiation transport have proven to be veritable road blocks.

With the extensive and homogeneous data sets which have become accessible in the last few years the general discussion of global parameters of SNe Ia is possible. The detailed statistics of luminosity, rise times, decline rates, and spectral line evolutions have made the systematic investigations of supernova energetics, explosive nucleosynthesis, and more detailed inferences on progenitors a possibility. The increased and coordinated access to telescopes of all sizes has brought the field forward substantially. With the statistics on global supernova parameters the tedious comparison with explosion models has been supplemented.

In the following an attempt is made to assemble the available information from the observations to point out future directions of SN Ia research.

5.1 Correlations

The differences of the various luminosity corrections and absorption determinations (see section 3.1) are very disconcerting. They clearly are not due to evolution, but will likely be traced to technicalities of the fits. The most obvious culprit is the degeneracy of reddening and intrinsic color of SNe Ia, which has to be lifted for a reliable measurement. The discrepancies apparent in Fig. 4 and discussed in section 3.1 are most likely due to this degeneracy. The influences on the cosmological conclusions drawn from SNe Ia will have to be investigated in much more detail and the discussion has already started (e.g. Drell et al. 1999). The different corrections also play an important role in the exact determinations of the Hubble Constant (Suntzeff et al. 1999, Jha et al. 1999, Saha et al. 1999, Gibson et al. 2000) and are responsible for the remaining discrepancies.

Despite the technicalities of the light curve fitting the variations among SNe Ia are real and have to be explained. It is very interesting to consider the invariants among SNe Ia. Each of them tells a different part of the overall story and should help in piecing it together.

With the brighter SNe seemingly rising and declining more slowly this implies that the energy release is retarded throughout the maximum phase. The width of the peak phase in the bolometric light curve also correlates with the peak luminosity (Contardo et al. 2000) and so does the occurrence of the shoulder (Contardo 2000). The more luminous objects are so through the whole known evolution, i.e. they are emitting more energy than the fainter supernovae. It is also striking to see that the very luminous SNe Ia show the characteristic Si II line appear relatively late (typically only after maximum light).

The color at maximum is a measure of the opacities in the ejecta. Since these are dominated mostly by lines and not continuum processes, the colors are not a direct indicator of the temperature in the ejecta (Pinto & Eastman 2000). Interestingly, the $B-V$ color is very well defined and depends very little on the light curve shape whereas $V-I$ shows a stronger dependence on the decline parameter (Phillips et al. 1999).

The velocities of the ejecta can be measured from the emission lines several months past the explosion (Mazzali et al. 1998). The fact, that they correlate with the light curve decline is remarkable. The ejecta velocities derived from the nebular lines are an indicator of the ratio of kinetic energy and total mass. Strictly speaking, this only applies exactly for spherically symmetric explosions, but at the late phases any asymmetry should be damped out. Since the decline correlates with the maximum luminosity and this in turn is connected to the Ni mass synthesized in the explosion (Arnett 1982, Arnett et al. 1985, Branch 1992) we have a direct connection of the explosion strength and a product of the power source of the supernova emission. More luminous SNe Ia also are more powerful explosions. The ejecta mass of these powerful explosions must be higher as well, as the slower release of the energy can only be achieved by a larger column density. This immediately rules out a single mass progenitor system.

The host galaxy morphology and the galaxy color provide information on the star formation of the parent population. SNe Ia in elliptical galaxies are on average less luminous than their counterparts in late spirals (Filippenko 1989, Hamuy et al. 1995, Schmidt et al. 1998). Also SNe Ia in bluer galaxies seem to be brighter (Branch et al. 1996). All of the most luminous objects (like SN 1991T) occurred in spiral galaxies, and most of them suffer reddening in the host galaxy and are possibly loosely connected to star forming regions or spiral arms (Bartunov et al. 1994). It thus appears as if the more luminous objects are connected to a younger parent population and the fainter SNe Ia come from old progenitor systems. Yet, the correction from the decline rates applies to all SNe Ia independent of the host galaxy morphology (Schmidt et al. 1998). Thus, although the parent population may be different, most likely due to age differences, most, if not all, SNe Ia come from the same type of progenitor system. It has been proposed that the explosion energy depends on the precursor composition and could be observed from samples which span sufficiently long look back times, i.e. shorter progenitor life times (Höflich et al. 1998b, Kobayashi et al. 1998, Umeda et al. 1999). Such experiments will require better and more extended data than are currently available.

The question of what is a normal SN Ia has been raised many times in the last few years (e.g. Branch et al. 1993). Selections based on color or spectra have been proposed and used. To what extent such subclassifications describe physical differences is, however, unclear.

The extreme cases of SN 1991bg and SN 1997cn can not yet be accommodated within the simple schemes proposed. Could it be that they emerge from different mechanisms? The answer is still outstanding and we need more objects of this sort to investigate.

5.2 Nickel masses

The nickel mass of individual supernovae differs by up to factors of several (section 3.4). With such large differences, it is clear that the explosions are not as uniform as assumed only a decade ago. It will be an important task for the next years to determine whether these differences are due to different explosion mechanisms (e.g. double detonations, deflagrations, etc.) or are variations of a single mechanism (e.g. the density at transition from deflagration to detonation (Höflich et al. 1996)). The distribution of nickel masses may provide a first indication of what the exact distribution of the explosions is. It has been claimed that most SNe Ia emerge from a fairly narrow range of luminosities (and hence nickel masses), but the numbers are still small. The distribution of the decline parameters has not yet yielded a clear picture (e.g. Drell et al. 1999).

It is of course also possible that we are observing two or more explosion mechanisms, each with variations on its own. A single explosion mechanism which produces differences of a factor of 10 as observed in the nickel masses (Table 1) has not been proposed yet.

5.3 Future developments

Three major questions about SNe Ia will have to be solved: the influence of reddening, the progenitor systems and the explosion mechanism. Observationally, reddening should be the easiest to either measure or avoid. Many interesting questions can be addressed with a statistically significant near-IR sample. The luminosity corrections are smaller in the I band (Phillips et al. 1999), at late times the near-IR is the prefered region for the determination of the Ni mass (Spyromilio et al. 1992, Bowers et al. 1997), and the near-IR Hubble diagram will also provide a reddening free determination of the Hubble constant. The reddening law in external galaxies will be another topic which could be addressed by SNe Ia observed in the optical and the near-IR.

Signatures of SN Ia progenitors should be discovered soon. Either signs of the companion transfer to the white dwarf are detected or possible progenitor systems can be ruled out on statistical grounds. Neither has so far been the case. Dedicated programs for the search of possible progenitor systems are needed.

The constraints on the progenitor models will have to be increased and improved. The fact that we do not know whether some SNe Ia come from sub-Chandrasekhar or Chandrasekhar mass explosions is embarrassing. In fact, not even the relative ejecta masses are known. If the above argumentation is correct (section 5.1), then we have a first sign of explosions with different masses.

The first direct detection of the $\gamma-$rays from the nuclear decay of ^{56}Ni and ^{56}Co would be a major success. Such a detection is within reach of the current instruments on CGRO or INTEGRAL (Höflich et al. 1998a, Georgii et al. 2000). The combination of the $\gamma-$ray detection with the observed (UVOIR) bolometric light curve will be a powerful tool to measure the escape fraction and hence the energy release in SNe Ia.

Statistical studies of the bolometric luminosity of SNe Ia will further delineate their true luminosity and hence nickel mass distribution. With such information it will become possible to decide what the major stellar evolution channels for SNe Ia are. We are entering an interesting phase, where searches will be volume limited even for faint SNe Ia and 'fair' samples can be established.

The future is bright for SN Ia research. The extension to high-redshift searches and the inherent possibility to probe SNe Ia over significant look back times offers the opportunity to follow a specific tracer of individual stars over a large fraction of the age of the Universe. This addition to the current supernova research will tell us about the history of stars beyond the cosmological implications championed so far.

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