OBSERVATIONS OF SUPERNOVAE[1]

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Abstract.
The available observations of the various types of supernovae are described and their connection with the current theoretical understanding outlined. We critically discuss the classification scheme employed for supernovae and point out its limits.

The observational homogeneity of type Ia supernovae has been challenged by recent, well-observed events. Nevertheless, the general characteristics are rather well described by models employing explosive carbon burning in white dwarfs. The most important input which observations should provide at this point is the mass of the progenitor star and the amount of radioactive nickel produced in the explosion. With reliable absolute magnitudes and improved model calculations becoming available such determinations appear in reach.

While the separate character of SNe Ib/c is now firmly established, too few objects have been observed detailed enough to probe the physical nature of these supernovae. The subclassification into SNe Ib and SNe Ic has not convincingly been proven. Paradoxically, the most valuable information on these supernovae has been provided by the observations of SNe II which switched to SNe Ib/c at late phases confirming the link between these two classes.

Observations of SNe II have revealed several distinct phases which are governed by different radiation mechanisms. Many details have been learned from SN 1987A and applied to other SNe II. The influences of size and mass of the progenitor star as well as the explosion energy on the evolution of the luminosity have been established. The additional powering of SNe II by conversion of kinetic energy into electromagnetic radiation in a dense circumstellar medium has revealed a new phase for these objects which starts several years after the explosion. Few cases have been observed where this energy source appears to be dominant at all times.

Key words: Supernovae, Formation of Neutron Stars

1. Introduction

The astrophysical significance of supernovae (SNe) is reflected in the many views astronomers have of them. These explosions mark the end of the nuclear energy production in massive (>10 $M_\odot$) stars and the start of the life as a neutron star, or are the disruption of a cooling white dwarf forced into explosive carbon burning. This for the star catastrophic event also affects the circum- and the interstellar medium through ionization and shock heating. The morphology of galaxies is influenced by the deposited energy, the chemistry changed by enrichment in metals, and

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stellar material recycled. The nucleosynthesis of all elements heavier than oxygen is provided by supernovae. Finally, supernovae have been employed as light beacons for cosmological distance measurements.

Observations of supernovae hence bear on many astrophysical issues, like stellar evolution, stellar mass loss, collapse and explosion physics, radiative hydrodynamics, shock physics, galactic structure and chemical evolution, and cosmology. There have been many excellent reviews in recent years. General overviews on supernovae are provided in the books by Petschek (1990), Wheeler et al. (1990), Woosley (1991), Danziger & Kjär (1991), and McCray (1994). Woosley and Weaver (1986) have presented the most complete description of the explosion physics of supernovae. Reviews dealing with more specific topics include Wheeler & Harkness (1990) on SNe I, Weiler & Sramek (1988) for radio supernovae, Arnett et al. (1989) and McCray (1993) for SN 1987A, van den Bergh & Tammann (1991) on supernova rates, Bartel (1985), Branch & Tammann (1992), and Schmidt (1993) for supernovae as distance indicators.

The observational tools available for the investigation of supernovae are also very diverse. Optical photometry and spectroscopy have contributed most information during the first decades of supernova studies. These data are now supplemented with observations at other wavelengths and, in the case of SN 1987A, even a neutrino detection. The different techniques provide insight into the various processes that occur in the explosion. The evolution of the spectrum (optical and near-IR) carries information on the chemical composition of the material taking part in the explosion. Some of this matter is not burned but merely accelerated, such as the envelope of a massive star after the core collapse. In other cases, the spectrum is composed of emission from the ashes of matter processed in the explosion. The line velocities can be used as diagnostic of the explosion energies. Optical photometry of supernovae provides insights into the overall energy radiated from the explosion and can disclose the power source. It is also sensitive to the energy source, the mass of the envelope, and the size of the progenitor star. Radio observations probe the circumstellar environment around the supernova and can provide important information on the newly-born pulsar through the evolution of the spectral index. X-ray observations have some bearing on the radioactive source powering the emission and indicate interaction with circumstellar material. Finally, γ-rays are direct measurements of the radioactive power source, the mass of the envelope in which the radioactive material is buried, and mixing of the stellar material with the ashes of the explosion.

Additional information has been gathered from supernova statistics and the morphology of, as well as the supernova position in, the parent galaxy. Within the limits of the spatial resolutions attained it is possible to derive parameters of the class of progenitor stars for different supernova types. Most recently the direct observations of the progenitors of SN 1987A and, possibly, SN 1993J have provided very important clues to what kind of stars end their lives in these explosive events. These observations provide much needed constraints on the explosions themselves, not to mention the surprises they represented.

Next I will describe the current classification scheme for supernovae and some secondary signatures of the various types (§2). The observational status of each of the different classes will be outlined separately. The evidence of white dwarfs as progenitors of SNe Ia is presented in §3. In section 4, a brief status on the observations of SNe Ib and SNe Ic is given. The discussion of SN 1993J then leads to the observations of SNe II (§4) and the link between the latter two classes. The summary (§5) discusses open questions.

2. Classification

Classification of supernovae should be based on a simple observational signature to distinguish different types. The physical implications of such a scheme can, however, be misleading and might not be too profound. Moreover, it is important to establish various examples of similar behavior, before a subclass can be created. Another aspect is to keep the scheme simple and not to involve too many observationally distinct methods for the definition of a class. The more complete information that is sought for the understanding of the individual objects or a closely defined group is stepping beyond any means of the classification scheme. In the above sense, classification of supernovae is a crude observational instrument for the separation of individual object groups.

Classification of supernovae was introduced by Minkowski (1941) to distinguish the two different spectral appearances of supernovae. The two classes were identified with well-observed supernovae, namely SN 1937C for Type I and SN 1940B for Type II. The latter had suspected emission of Hα near maximum and later "resembles" normal novae. The spectra of SNe I were not well understood but recognizable by their "very wide emission bands." The classification system was further refined by Zwicky (1965) with three additional classes. Since these three classes had only one known representative each, they were dismissed by Minkowski (1964) and Oke & Searle (1973).

Modern supernova classification has been summarized by Harkness & Wheeler (1990). It is based on spectroscopic observations near maximum light. Three main types are distinguished (cf. Figure 1): type Ia, defined by the absence of hydrogen lines in their spectra and the presence of a Si II absorption near 6100 Å, type Ib and Ic both lacking H lines and the Si feature but displaying, in the case of SNe Ic very weak, He lines, and type II which encompass all SNe with hydrogen lines. The spectral evolution of SNe Ia produces spectra a few weeks past maximum which resemble SNe Ib near peak light. This has caused confusion in a few cases and points to the need of careful analysis of the spectra for classification. A separation between SNe Ib, helium-rich, and SNe Ic, helium-poor, is proposed (Wheeler et al. 1987, Wheeler & Swartz 1994). Whether there is a continuous variation from one subclass to the other or a clear dichotomy of objects is still undecided.

Secondary indicators for the classification schemes are becoming more apparent with more data and better theoretical understanding of the explosions and their stellar progenitors. So are the spectra several months past maximum rather homogeneous for SNe Ia with many broad lines of Fe-peak elements, while SNe II display distinctive emission lines of Hα, [O I] and [O III]. SNe Ib and SNe Ic, with broad forbidden lines of oxygen and calcium, are indistinguishable from each other at this epoch. There have been, however, intriguing cases of SNe II changing to what normally are typical spectra of SNe Ib/c at this phase. The two well-documented cases

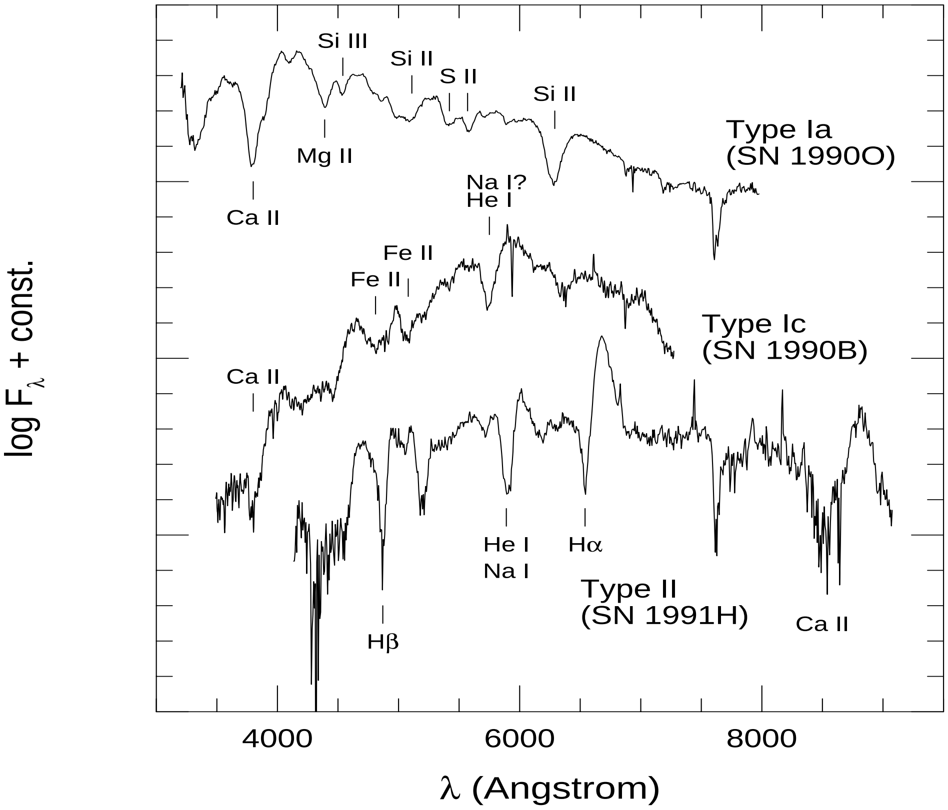

Fig. 1. Sample spectra near maximum for the main supernova types

are SN 1987K (Filippenko 1988) and SN 1993J (e.g. Wheeler & Filippenko 1994). These objects represent important links between different classes for the physical understanding of supernovae.

While the optical light curves of SNe II have been rather distinctive and prompted a subclassification into linear and plateau-like light curves (Barbon et al. 1979), SNe Ia and SNe Ib/c display nearly indistinguishable light curve shapes (Ensman & Woosley 1988, Leibundgut 1988). Although the colors are much redder in the case of SNe Ib/c, this selection criterion is spoiled by the often unknown extinction toward the objects. The shape of the near-infrared (JHK) light curves appears to separate the two subclasses of SNe I (Elias et al. 1985), but some peculiar SNe Ia have shown intermediate shapes (Frogel et al. 1987).

Radio emission from supernovae is normally associated with circumstellar material (Chevalier 1990). No SN Ia has been observed at these wavelengths. A clear separation between SNe Ib/c and SNe II has been established (Van Dyk et al. 1993a). There appears to be a subgroup of SNe II with clearly distinct radio light curve shapes (Weiler et al. 1990, Van Dyk et al. 1993b).

The connection of the classification scheme with the physics of the explosions is not straightforward. As described below, SNe II are thought to be displays of core

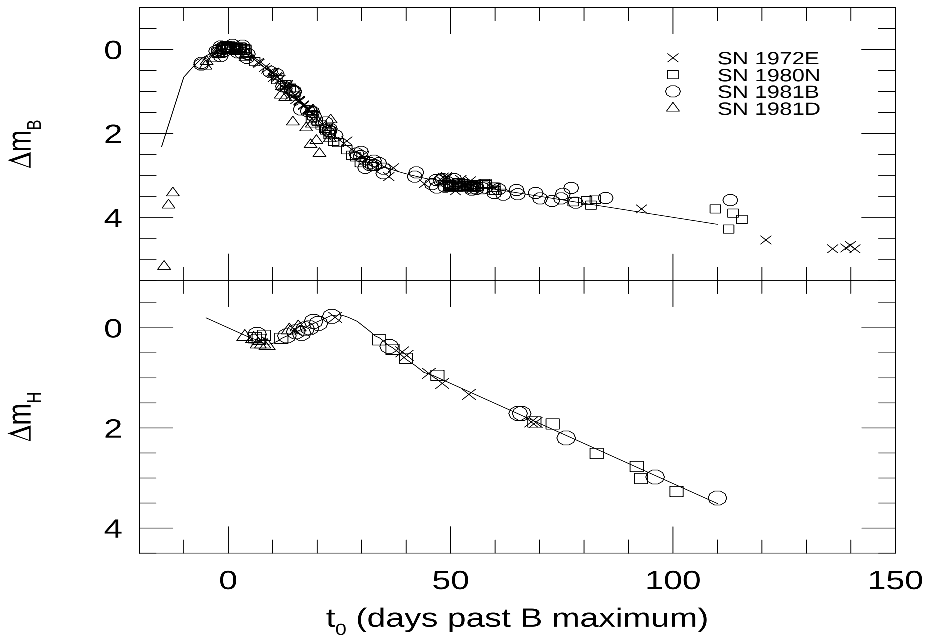

Fig. 2. Optical and near-infrared light curves of SNe Ia (from Leibundgut 1988)

collapses in massive stars, while SNe Ia are more likely the explosive burning of a white dwarf. The observations of SN 1993J and SN 1987K link the SNe Ib/c with SNe II and indicate that the former are also core collapses rather than variations of explosions in white dwarfs, despite the similarities observed in the optical spectra and the photometry. These cases demonstrate the limitations of the classification scheme employed for supernovae for the underlying physics.

3. Type Ia Supernovae

Historically these supernovae have been described as extremely uniform in their appearance. This has been based on the light curve shapes, the observed colors, the peak luminosities, and the spectral evolution. In the last few years this homogeneity has cracked under new investigations and peculiar events of the class.

The light curve shapes of SNe Ia are remarkably similar in the optical and near-infrared broad-band photometry (UBVJHK; Leibundgut 1988). Many events adhere to a unique light curve shape (Leibundgut et al. 1991b). Peculiar objects, like SN 1939B (e.g. Minkowski 1964) and SN 1986G (Phillips et al. 1987, Frogel et al. 1987), even though exhibiting clearly discrepant light curves, had been disregarded. Recently, Phillips (1993a) pointed out that also the optical light curves are not as uniform as assumed. The decline during the first 15 days after maximum ranges from 1.5 mag to 2.5 mag for a set of nine supernovae, an effect confirmed in an independent analysis by Vacca & Leibundgut (1994) for a much larger sample and a more detailed fitting procedure. Furthermore, Suntzeff (1994) has shown that the R and I light curves of SNe Ia do not follow a unique shape, but rather are individual for most SNe Ia. The colors of SNe Ia display some variation, but the scatter is remarkably small (e.g. σ(B-V)=0.22 mag for 24 supernovae, Leibundgut 1991) considering extinction which probably affects some of the supernovae. The value of the intrinsic color (e.g. $(B\text{-}V)_0$) is still a matter of debate (Pskovskii 1968, Cadonau et al. 1985, Capaccioli et al. 1990, Hamuy et al. 1991, Sandage & Tammann 1993) with the more recent determinations favoring a value of $(B\text{-}V)_0 \approx 0.0$ mag.

The spectra of SNe Ia are dominated by many lines of intermediate-mass elements like Si, S, Mg, and Ca near maximum light (Branch 1990). With more accurate observations in recent years it has become obvious that significant variations exist in the line strengths among individual objects near maximum (e.g. Filippenko et al. 1992a, b, Phillips et al. 1992, Leibundgut et al. 1993b, Phillips 1993b, Branch et al. 1993). Figure 3 illustrates this point. About a month later the continuum emission disappears and is replaced by broad emission lines of many iron-peak elements (Axelrod 1980, Pinto 1988). At about seven weeks past peak light the spectra appear virtually identical (Filippenko et al. 1992b, Leibundgut et al. 1993b). This is a strong indication that the ashes are very similar and the explosion mechanism rather unique.

A "standard" model was devised to explain most of the above observations and also account for the fact that SNe Ia were observed in elliptical galaxies and in the halos of spiral galaxies, which are presumably composed of old stars. In this model (cf. Woosley & Weaver 1986, Wheeler & Harkness 1990 for reviews) a white dwarf is incinerated by explosive carbon burning. The triggering of the explosion takes place when the white dwarf is nudged over the Chandrasekhar mass ($\sim$1.4 $M_\odot$) and the density and temperature in the center of the star become high enough to start the burning. The optical display of the supernova is then entirely due to heating from radioactive decays of ^{56}Ni and ^{56}Co nuclei. This model has been very successful in describing most of the available observations. With the basically unique configuration of the precursor system a satisfactory homogeneity in appearance is guaranteed. The fact that only "processed" material is observed in the spectra is explained by the burning front converting most material into nuclear statistical equilibrium, i.e. iron-peak elements. The tracers of intermediate-mass elements observed in the early-time spectra are due to the dying out of the subsonic flame and incomplete burning near the surface of the white dwarf. The differences in the maximum-light spectra can be explained by small variations as the flame peters out and might arise from only tiny amounts of matter. At late times, when the explosion becomes transparent, we are truly looking at the ashes. No circumstellar material is expected around a white dwarf and thus the lack of radio detections (Weiler et al. 1986) is accounted for naturally. As end-products of stellar evolution white dwarfs represent an old population which concurs with their non-association with star forming regions (Maza & van den Bergh 1976).

The above model is further supported by the agreement reached from spectral modeling at early and late epochs (Harkness 1991a, b, Jeffery et al. 1992, Mazzali et al. 1993, Axelrod 1980, Pinto 1988). The fast decay of the late-time bolometric light curve is readily explained by the escape of γ-rays from the ejecta, pointing to a small mass (Leibundgut & Pinto 1992). Detailed calculations of the photospheric

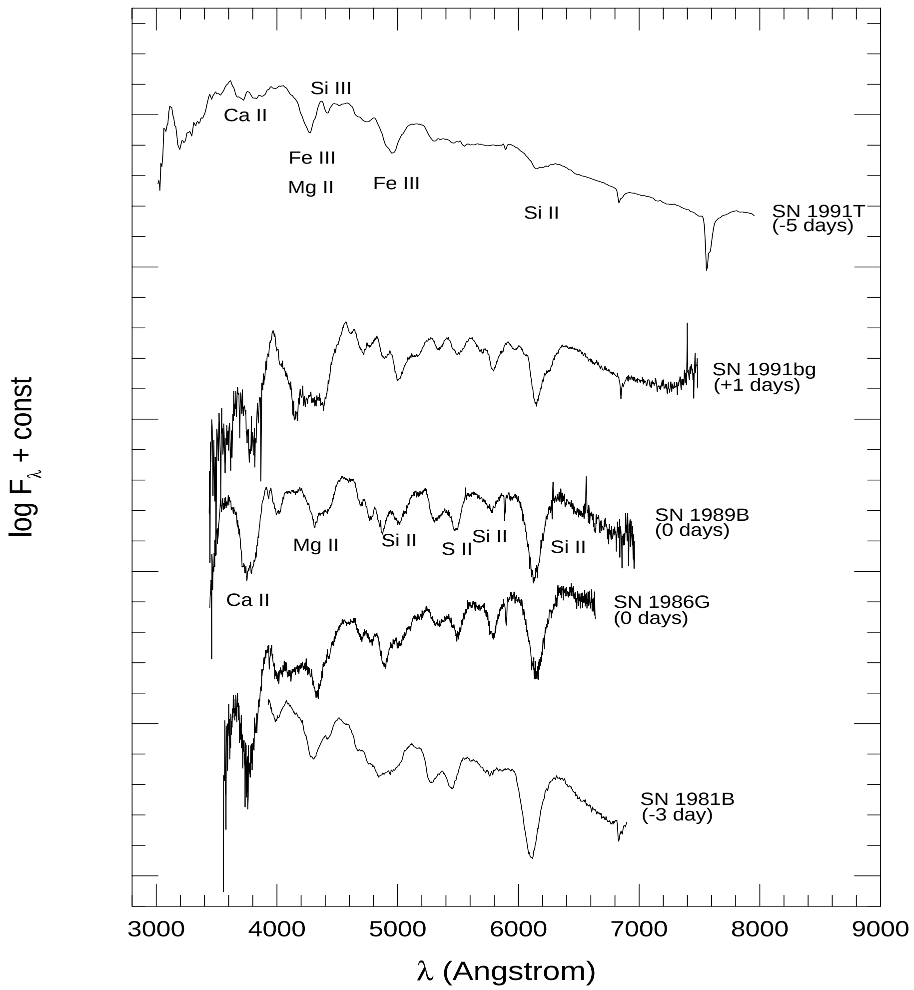

Fig. 3. Spectra of SNe Ia near maximum (from Leibundgut et al. 1993b)

peak phase of supernova light curves have recently succeeded in reproducing the observations (Khokhlov et al. 1993, Höflich et al. 1993). A crucial parameter is the rise time from explosion to maximum light and certain models now can match the observations (Leibundgut 1994a). The most direct evidence of the radioactive power source, however, comes from a study of Co and Fe lines several weeks past maximum (Kuchner et al. 1994). The line ratios follow exactly the predictions of the decay times determined by nuclear physics.

Although the "standard" model can explain many aspects of SNe Ia, it has its shortfalls. Since the white dwarf has to accrete matter, there must be a companion star. The lack of radio emission indicates that not much matter is lost by this star, which excludes giant star companions. Any hydrogen and helium accreted onto the white dwarf has to be processed quickly enough or it would show up in early time spectra. Unfortunately, there are no good limits on the H mass on top of a SN Ia from the observations. Double-degenerate systems, in which two degenerate white dwarfs merge have been adopted instead as the canonical model (Iben & Tutukov 1984, Webbink 1984, Tutukov et al. 1992). The dynamical time scales and the formation of a disk in the merger are not easily explained in these models. Furthermore, there have been no candidate systems observed despite extensive searches (Bragaglia et al. 1990, Renzini 1994). Another problem with the Chandrasekhar-mass white dwarfs is the observed mass distribution of white dwarfs (Bergeron et al. 1992). There is only one white dwarf with a mass above $1M_\odot$, which probably is already a merged object. Thus, at least $0.4M_\odot$ would have to be accreted to build a Chandrasekhar-mass white dwarf.

Other problems include the IR light curves which display conspicuous minima about a week after the optical maxima (Fig. 2). Similar dips are also observed in R and I light curves (Ford et al. 1993, Hamuy et al. 1993, Suntzeff 1994). The reason for this flux redistribution has not yet been addressed in model calculations. Direct determinations of the Ni mass from late-time spectra also point to rather large differences in the Ni production contrary to the predictions from models (Ruiz-Lapuente & Lucy 1992). Large variations in the expansion velocities as measured from Doppler displacement of absorption lines (Branch et al. 1988, Branch & van den Bergh 1993) indicate variations in the explosion energies.

The most severe challenge for the "standard" model arouse recently from detailed observations of SN 1991T (Filippenko et al. 1992a, Ruiz-Lapuente et al. 1992, Phillips et al. 1992) and SN 1991bg (Filippenko et al. 1992b, Leibundgut et al. 1993b). Both objects displayed differences in the light curve shapes and spectral peculiarities. In the case of SN 1991bg there are very severe discrepancies in the late time spectrum as well (Filippenko et al. 1992b, Leibundgut et al. 1993b, Ruiz-Lapuente et al. 1993). Such variations cannot be explained within the standard framework of the explosion of a Chandrasekhar-mass white dwarf.

An important conclusion from the observations is that most of the material has been burned in the explosion and hydrogen and helium are absent, the radioactive power source appears now well established, and a low ejecta mass is deduced from the decline in the late-time light curve. All this points toward a white dwarf progenitor for SNe Ia, but none of the above signatures provides a quantitative measure of the total mass or the amount of radioactive ^{56}Ni synthesized. This has prompted models which employ small-mass white dwarfs in the explosions (Shigeyama et al. 1992, Woosley & Weaver 1994). With the physics available for off-center explosions (Livne 1990, Livne & Glasner 1991, Woosley & Weaver 1994) it might be possible to explain simultaneously the apparent homogeneity of the bulk of the objects and the deviations of a few supernovae from this norm.

A frequent application of SNe Ia has been the determination of cosmological distances and the derivation of the Hubble constant H_0 (Branch & Tammann 1992, and references therein). To achieve meaningful results two conditions have to be met. First, the narrow range of peak luminosities of SNe Ia has to be established reliably, and, second, the absolute value of this peak luminosity has to be determined.

Establishing the standard candle character of supernovae primarily means that they reach the same luminosity at maximum. Further indications of the homogeneity of the class in its appearance provide additional arguments, but are not essential for the use as distance indicators. Several groups have measured the observed luminosity distribution of SNe Ia at maximum (Tammann & Leibundgut 1990, Della Valle & Panagia 1992, Branch & Miller 1993, Sandage & Tammann 1993) and agree fairly well with each other. There is little doubt that by appropriate treatment of "outliers" a tight distribution around a mean absolute magnitude can be established. There has been some concern about difficult it is to sort out the "peculiar" supernovae, but Branch et al. (1993) argue that the spectroscopic signatures are clear enough for a separation. For many SNe Ia observed in the 1960's and 1970's, however, not enough data are available to assess their status and most of the above derivations rely on data samples which include many of those SNe. An additional complication is the often unknown extinction toward SNe Ia. The effect of this has been discussed in Leibundgut & Pinto (1992). Unfortunately, errors of up to 40% can be incurred in the determination of the mean of the distribution of the peak luminosity of SNe Ia.

The most reliable measurement of the absolute luminosity of a SN Ia is by Saha et al. (1994) for SN 1937C. They have measured cepheids within IC 4182 and established the distance to this galaxy. A different route is the calculation of the luminosity from models pioneered by Arnett et al. (1985). Branch (1992) has gathered what he considered the best determinations of this kind. An independent investigation involving a variety of models has been presented by Leibundgut & Pinto (1992). They conclude that as long as we are not able to select the "best" model, a large uncertainty has to be accepted. All models considered, however, employed the explosion of Chandrasekhar-mass white dwarfs. With smaller mass explosions the luminosities are decreased. A slightly different approach was used by Müller & Höflich (1994) who find a suitable model for each individual supernova and thus individual luminosities to determine H_0. No assumption on the standard character of SNe Ia is made.

No value of H_0 is quoted here and the reader referred to the literature. Discussion of the various error sources is desperately needed to solve some of the outstanding problems.

4. Type Ib/c Supernovae

Only recognized about a decade ago as a separate subclass among SNe I (Wheeler & Levreault 1985, Uomoto & Kirshner 1985, Panagia 1985) this group of objects might represent the "cross-dressing" case of supernovae. Around maximum they resemble SNe Ia in their photometric and spectroscopic appearance, but their late-time spectra and radio signatures are related to SNe II. With two examples of SNe II which actually have "changed type" (SN 1987K and SN 1993J) the latter connection has been further strengthened.

The observational data for this class are rather scanty. The general characteristics have been summarized by Porter & Filippenko (1987). The question whether there is the need for a further subclassification remains open. Swartz et al. (1993) argue from model calculations for a clear distinction between SNe Ib (He-rich) and SNe Ic (He-poor) on the basis of the He mass observed in the spectra. In addition, Wheeler

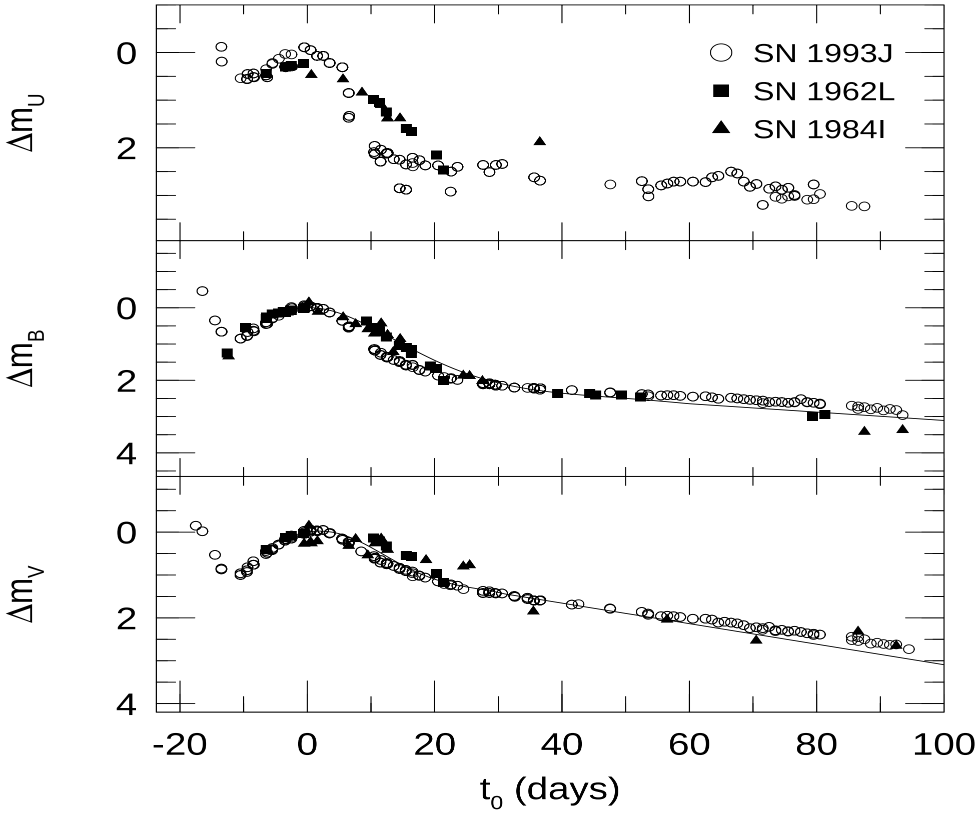

Fig. 4. Optical light curves of the type Ib/c SN 1962L (Bertola 1964) and SN 1984I (Leibundgut et al. 1990) compared with SN 1993J (Richmond et al. 1994); the line represents a mean curve for SNe Ib/c from Leibundgut (1988)

& Swartz (1994) find SNe Ib of higher mass than SNe Ic.

The spectroscopic evolution is dominated by He lines for the Ib supernovae while in SNe Ic absorption lines of predominantly C, O, Ca, and Fe are observed (Wheeler et al. 1987). Faint Balmer lines of H are suspected, but not a clear signal has been detected (Jeffery et al. 1991, Filippenko 1992). After about 6 months the nebular spectra show strong Ca and O emission lines (Filippenko et al. 1986, Filippenko et al. 1989).

The optical light curves are very similar to the ones of SNe Ia (Ensman & Woosley 1988, Leibundgut 1988). The infrared light curves, however, do not exhibit the second maximum and are rather distinct (Elias et al. 1985).

If SNe Ib/c emerge from massive stars and are caused by a core collapse, as is suggested by their connection with SNe II, the light curves are expected to display a sharp early peak from the shock break out at the surface of the star. This has never been observed in a SN Ib/c proper, but SN 1993J had been detected early enough (Figure 4). It is clear from this figure that the light curve shapes of SN 1993J are indeed very similar to the ones of SNe Ib/c. A similar conclusion has been found for the bolometric light curve of SN 1993J and SN 1983N (Nomoto et al. 1993, Richmond et al. 1994). For the comparison in Fig. 4 the curves have been shifted to coincide at the maximum of the broad peak. The peak for SN 1962L and SN 1984I is evidently broader in all bands and the slope of the decline 30 days past maximum steeper. The occurrence of the maximum in U seems also shifted to later times, although the data are really not sufficient for a clear result. The first B observations of SN 1984I and SN 1962L, an estimate of a non-standard band photograph however, are very interesting as they lie at the bottom of the dip in the SN 1993J light curve. Both these supernovae might have been caught shortly after the the initial peak of shock breakout. A duration of a few days is not excluded by the observations; an upper limit about 2 mag fainter than the B peak brightness was determined 14 days before the first detection of SN 1984I (Leibundgut et al. 1990). The broader peak of the SN Ib/c indicates a slower release of the energy diffusing out of the core than for SN 1993J. The steeper slope at late times on the other hand points toward a faster increase in γ-ray transparency of the envelope. With similar explosion energies this implies a smaller mass in the envelopes of SN 1962L and SN 1984I than for SN 1993J.

SNe Ib/c are not clearly stronger associated with star forming regions (Van Dyk 1992). It appears as if they are not the very massive stars (> 30 $M_\odot$) which were suspected in the beginning (e.g. Ensman & Woosley 1988, Schaefer et al. 1987). A model where the star has lost its hydrogen envelope due to binary interaction appears more likely (Shigeyama et al. 1990) and is further supported by the apparent connection of SN 1993J with SNe Ib/c. Additional support for such a model, as opposed to one with white dwarfs, is the radio emission from these objects (Van Dyk et al. 1993a). If the connection to SNe II is confirmed, this means that SNe Ib/c contribute to the population of neutron stars.

5. Type II Supernovae

This class of supernovae comprises a great many individual examples of objects displaying hydrogen in their spectra. The additional subclassification into plateau (II-P) and linear (II-L) events (Barbon et al. 1979, Doggett & Branch 1985, Patat et al. 1993) is based on photometry rather than spectroscopy. A connection of these photometric types with spectroscopic features has been proposed and consists mainly in the shape of the line profiles in maximum-light spectra, but has not yet been unambiguously proven (Harkness & Wheeler 1990). Also grouped in this class are objects with rather narrow ($\sim$1000 km/s) emission lines of mainly hydrogen and helium. These events have been proposed for a separate subtype (Schlegel 1990), but only a few examples have been observed near maximum light. It might also be that the emission of these objects is not powered by energy deposited by the explosion in the envelope, but rather originates in the interaction of the explosion shock with surrounding material (Chevalier 1990, Filippenko 1991, Stathakis & Sadler 1991, Chugai & Danziger 1993, Leibundgut 1994b). A conjecture supported by the strong radio emission from these objects (Weiler et al. 1990, Van Dyk et al. 1993b).

In the following we will discuss the physical processes dominating the light curve of a "generic" type II supernova and point out the most prominent deviations observed to date. Much of the details have been learned from SN 1987A and the reader is referred to the relevant literature.

The optical display of a type II supernova starts with the shock breaking out at the surface of the progenitor star a few hours after core collapse. Up to this moment the star looks like any evolved supergiant, since at advanced burning stages the envelope does not have enough time to adjust to the rapid changes in the core. With the initial X-ray and UV burst the light curve peaks within hours of the core collapse before the cooling of the atmosphere decreases the flux very rapidly. The only observations of this phase we have to date are from SN 1987A (Kirshner et al. 1987, Arnett et al. 1989) and SN 1993J (cf. Wheeler & Filippenko 1994). For stars with expanded envelopes (red supergiants) this phase lasts longer than for more compact progenitors (Falk & Arnett 1977, Klein & Chevalier 1978). The rapid fading following the peak is only stopped when the photosphere is balanced by the expansion of the ejecta. This results in the plateau phase lasting as long as the photosphere recedes through the envelope. The length of the plateau is mainly a function of the depth of the envelope, i.e. envelope mass, and the explosion energy, and thus the expansion velocity of the ejecta (Chugai 1991, Popov 1993, Hsu et al. 1993). During this phase the colors of the supernova tend to remain constant implying a constant temperature (Schmidt et al. 1992). Once the photosphere has receded deep enough to encounter the additional heating from the radioactive decay of ^{56}Ni and ^{56}Co the plateau is extended for a short time (Woosley & Weaver 1986, Hsu et al. 1993), before the light curve starts declining. The transition between the plateau and the decline phase is determined by the decreasing optical depth to optical photons. For stars with massive envelopes all the energy released by the ^{56}Ni – ^{56}Co – ^{56}Fe decay chain is converted into optical emission and the bolometric light curve approaches a decline rate corresponding to the life-time of ^{56}Co (Suntzeff & Bouchet 1990, Turatto et al. 1990, Schmidt et al. 1993).

The deviations of SN 1987A and SN 1993J from this general picture point to different progenitor stars. SN 1987A was the explosion of a compact blue supergiant and much of the explosion energy went into overcoming the large potential energy. Thus, the photosphere receded very rapidly and no plateau was formed. The second broad maximum in the light curve was produced by the heating from the ^{56}Ni and ^{56}Co decays. The large envelope mass resulted in the extended peak for this supernova. In the case of SN 1993J a rather small envelope mass prevented the formation of an extended recombination period and the second maximum was again formed by the diffusion wave from the radioactive decays. The reduced length of this peak also indicates a small envelope.

The decline rate at late times might be changed by dust formation (Lucy et al. 1991, Meikle et al. 1993) and the ionization freeze-out (Fransson & Kozma 1993) as observed in SN 1987A. The former shifts the flux from optical wavelengths into the infrared by heating of newly formed dust grains, while the second effect arises from the fact that the time of de-excitation of atoms becomes comparable to the expansion time of the supernova and this additionally "stored" energy becomes visible. Although probably not uncommon in other supernovae, these processes have been observed only in SN 1987A where they occurred $\sim$6 and $\sim$12 magnitudes below peak brightness, respectively.

Figure 5 displays the spectral evolution of SN 1990E, a rather typical SN II with well-defined P Cygni profiles of the hydrogen lines around maximum (Schmidt et

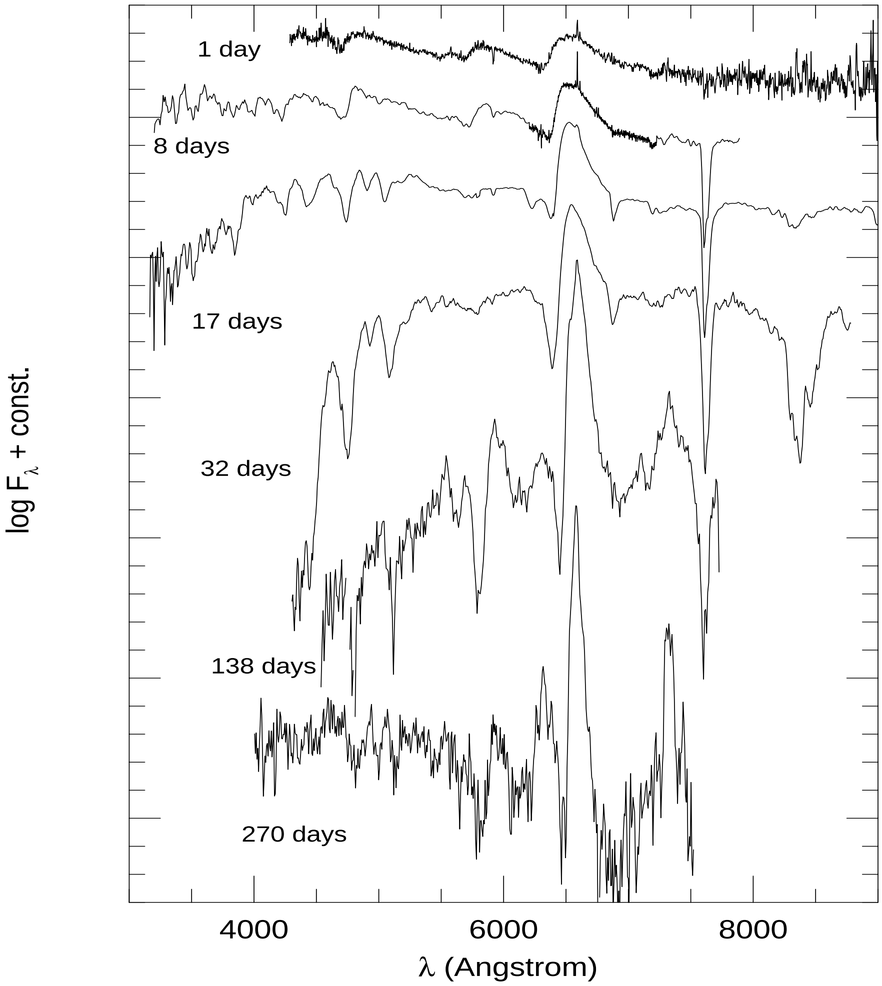

Fig. 5. Spectra of SN 1990E (from Schmidt et al. 1993). The phases are given as days past the optical maximum.

al. 1993). In the first spectrum only helium and hydrogen lines are present as the supernova still cools from the shock-heating of the envelope. During the plateau phase, which lasted from about 15 to 100 days past explosion, the spectrum changes only little with weaker lines becoming more apparent as the photosphere moves inward to slower material. Calcium and iron lines appear when the recombination front moves through layers rich in these elements. The line profiles persist for the time the supernova remains on the plateau of the light curve. SN 1990E disappeared behind the sun about one month after discovery and was observable only 100 days later (Schmidt et al. 1993, Gomez & Lopez 1993, Benetti et al. 1994). Entering the nebular phase the supernova displayed very strong Hα emission along with weaker

[O I] emission also observed in other SNe II (Branch et al. 1981 (SN 1979C], Uomoto & Kirshner 1986 [SN 1980K], Phillips & Williams 1991, Spyromilio et al. 1991 [SN 1987A]). For a few months the Na D lines form a very strong P Cygni line. The emission near 7300 Å is either from [Ca II] or [O II] lines and is fairly typical for SNe II.

The evolution of the line luminosity in Hα is a very sensitive measure of additional energy sources which might become important at late phases (Chugai 1990). For most supernovae this implies that there is indeed an additional power source (Chugai 1990, Schmidt et al. 1993, Gomez & Lopez 1993, Benetti et al. 1994). Prime candidates are long-lived radio-isotopes like ^{57}Co, ^{22}Na, and ^{44}Ti (Woosley et al. 1989), a buried pulsar loosing angular momentum and ionizing a plerion (Pacini & Salvati 1981, Chevalier & Fransson 1992), light echos (Chevalier 1986, Chugai 1992), and shock-interaction with circumstellar matter (Chevalier 1990, Chugai 1992, Chevalier & Fransson 1994). Such changes have been observed in a few supernovae several years past explosion, most prominently in SN 1980K (Fesen & Becker 1990, Leibundgut et al. 1991a, Uomoto 1991, Leibundgut et al. 1993a) where the emission has remained steady at V$\approx$23 mag for the last three years. Other supernovae with similar light curves might be SN 1979C (Fesen & Matonick 1993) and SN 1970G (Fesen 1993). The most likely energy source in these cases is the shock heating the circumstellar material lost by the progenitor star as a stellar wind (Chevalier & Fransson 1994, Leibundgut 1994b). In these objects the strong explosion shock is traveling in the dense circumstellar environment and excites this material. At the same time the shock is decelerated and a second shock front emerges where the expanding debris encounters the slower, shocked matter (Chevalier 1990). One of the main signatures of such a process is its radio emission (Chevalier 1982), which has been observed for all supernovae with optical detection a few years past maximum (Leibundgut 1994b). The spectra display broad ($\sim$5000 km s^{-1}) lines of hydrogen, oxygen, and possibly calcium (Fesen & Becker 1990, Leibundgut et al. 1991a). SN 1980K has reached a constant flux level about 2 years after explosion and remained a this luminosity for at least a decade (Leibundgut et al. 1993a). It appears that only the kinetic energy ($\sim$10^{51} erg) can provide the energy pool required. A pulsar could sustain the emission at the same level, but narrow ($\sim$1000 km s^{-1}) lines are predicted from such a power source (Chevalier & Fransson 1992). Other signatures for shock interaction with circumstellar matter include narrow emission lines at early times, when the circumstellar material is ionized by the shock breakout, observed from the ring in SN 1987A (Fransson et al. 1989) and SN 1993J (cf. Wheeler & Filippenko 1994), infrared echoes, observed for SN 1980K (Dwek 1983), as well as blue continua, UV, and X-ray emission at early phases as proposed by Fransson (1984). Many questions remain unanswered at this time. The constancy of the emission from SN 1980K cannot be accommodated by the models, at the same time a sudden drop in luminosity observed in SN 1957D (Long et al. 1992) remains unexplained. Potentially this late emission probes the composition and conditions in the stellar wind, but we are simultaneously observing the heated debris of the explosion. To disentangle the contribution of the two emission sites from the inner and outer shock requires additional modeling.

A small group of SNe II displays remarkable deviations from the above scenario.

The peaks of their light curves have never been observed and their decline rates are much smaller than what is expected from ^{56}Co decays. The best observed examples to date are SN 1978K (Ryder et al. 1993), SN 1986J (Rupen et al. 1987, Leibundgut et al. 1991a), SN 1987F (Filippenko 1989), and SN 1988Z (Stathakis & Sadler 1991, Filippenko 1991, Turatto et al. 1993). Although only SN 1988Z has a well-observed light curve (Turatto et al. 1993), the slow decline rates are also reflected in the evolution of line fluxes (Filippenko 1989, Leibundgut et al. 1991a, Turatto et al. 1993). The nature of the emission and its power source are not resolved, but interaction with a very dense material close to the supernova is most likely (Filippenko 1991, Chugai and Danziger 1993). All known objects of this class are evolving very slowly (Leibundgut 1994b). It appears as if the interactions with the pre-supernova wind dominates the light curve from the start thus obliterating other processes. For SN 1986J mostly narrow ($\sim$1000 km s^{-1}) lines of hydrogen, helium, and Fe were observed. At the same time the oxygen lines are broader ($\sim$2000 km s^{-1}; Leibundgut et al. 1991a). The line ratios in the oxygen lines indicated very dense ($n_{O\ I} \approx 10^9$ cm^{-3}) and cold (T$\approx$4000 K) material in the ejecta with only a very small filling factor ($<10^{-3}$). Interestingly, the oxygen emission is not fading, although the Hα flux decreases. While SN 1986J has been discovered probably only several years after the explosion (Weiler et al. 1990, Bartel et al. 1991) and suffers from a large, and undetermined, extinction within its parent galaxy, SN 1988Z has been detected at the latest half a year after explosion and lent itself to more detailed studies (Stathakis & Sadler 1991, Filippenko 1991, Turatto et al. 1993). At early times a broad component of the Hα lines indicates high expansion velocities ($\sim$40000 km s^{-1}) and a narrow component of only a few 1000 km s^{-1}. As in SN 1986J narrow lines of H, He, N, and Fe were observed, but also broad lines of Ca were detected. Many Fe lines are present in a broad emission feature near 5300 Å (Chugai 1994). The strong, narrow Hα lines reached a maximum only $\sim$400 days past discovery at $\sim$10^{41} erg s^{-1} and declined only very slowly (Turatto et al. 1993). The radiated energies are very high for all these objects ($>$10^{39} erg s^{-1}). They are also the brightest supernovae observed in the radio which indicates very strong shocks in dense material (Weiler et al. 1990, Van Dyk et al. 1993b). It is as yet unclear from which stellar progenitor systems these supernovae arise.

The use of SNe II for distance measurements has been boosted considerably with the new models which became available stimulated by the explosion of SN 1987A. This object at a known distance provided a perfect opportunity to test the ability of models to match the observations and in addition predict the luminosity evolution. Using SNe II for distance determinations had been proposed a few decades ago (Kirshner & Kwan 1974), but had to await improvements in the spectral modeling to yield accurate results (Schmidt et al. 1992). The application is known as Baade-Wesselink method for the determination of distances toward pulsating stars. For supernovae it is modified to calculate the total flux from hydrodynamical models of the explosion and assumes homologous expansion of the photosphere. The observed flux is proportional to the absolute luminosity divided by the square of the distance to the object. The luminosity of the supernova depends on the size of the photosphere and its temperature (assuming a radiation close to a blackbody), which in turn changes with the expansion of the photosphere. Thus, a relation can be formed that links the time since explosion with the distance and the observable quantities expansion velocity, color, and apparent magnitude (Schmidt et al. 1992). For a successful application the models had to provide information on how to determine the expansion velocities and how the radiation deviates from a pure blackbody. The first problem has been solved with the recognition that lines with small optical depths arise much closer to the photosphere than strong lines of hydrogen (Eastman & Kirshner 1989). For the second problem a whole suite of models has to be calculated and the corrections determined for different temperatures. During the plateau (photospheric) phase of SNe II these calculations have been established reliably. This procedure can easily be tested with supernovae at known distances and has produced very convincing results. A warning on the limits of the method was issued by the determination of the distance toward SN 1993J (see Wheeler & Filippenko 1994 for a summary). In this case specific models complying with the peculiar nature of the supernova had to be constructed in order to achieve reasonable results.

The method has been applied to nearly 20 supernovae out to a distance of 180 Mpc (Schmidt 1993). Major limitations are the faintness of the objects and the lack of sufficient photometric and spectroscopic coverage during the plateau phase. The value of H_0 derived by this method is 75 ± 10 km s^{-1} Mpc^{-1} (Schmidt 1993).

6. Summary

The expression "supernova" really stands for two different kinds of explosive events at the end stages of stellar evolution. The explosive burning of a white dwarf, probably triggered by mass transfer, does not leave a compact remnant. On the other hand the core collapse in massive stars initiates the violent display called type II supernovae, and is probably also responsible for SNe Ib/c. The main difference between the latter classes might be the amount of hydrogen left in the envelope at the time of explosion. The classification system, as it is used today, has reached its limits for it no longer reflects the underlying physical processes.

The conditions of a star when it is disrupted strongly influence the appearance of the supernova. Size, mass, and chemical composition imprint themselves into the electromagnetic display of the explosion.

SNe Ia appear to be fairly well understood and most of the observations can be readily interpreted. Important questions at this point include the stellar evolution leading to progenitor systems, the mass of the exploding white dwarf, and how much radioactive fuel is produced in the burning. Recent direct determinations of absolute magnitudes (Saha et al. 1994), in connection with improved model calculations (Höflich et al. 1993), will provide much needed insight. The variations among SNe Ia will have to be explained, but there is room within the framework of explosive burning of white dwarfs for such peculiar objects. The implications of these results for the distance determinations are profound.

SNe Ib and SNe Ic are in the poorest observational state of all classes. Not enough objects have been sufficiently observed for stringent conclusions. It is not even clear whether the subtype Ic is appropriate or whether these objects are just variants of SNe Ib. The link with SNe II has become very strong with at least two known supernovae evolving from Type II to Type Ib/c at late epochs. Nevertheless, we do not know much about the stars that end their lives in these explosions, nor how frequent these supernovae are (cf. Strom 1994, Muller et al. 1992, Cappellaro et al. 1993 for this debate). More and better data are desperately needed.

SNe II are well explained as the results of core collapses. A new phase for these supernovae is observed through their interaction with the circumstellar medium they are placed in. The conversion of kinetic energy into radiation sustains the emission from these objects for decades. The detailed physics have still to be worked out, especially the contributions from the inner and outer shock have to be disentangled. Some rare events do show prominent deviations from the general picture. Their high X-ray, optical, and radio luminosities, slow evolution, and narrow lines indicate interaction with a very dense circumstellar environment. First interpretations of the observations have been advanced, but we are still far from a detailed understanding.

And then there are new surprises in store. The more supernovae with detailed observations become available the more nature proves to be more innovative than human mind. The best-observed supernovae do not fit the previously defined classes. SN 1885A (S And; de Vaucouleurs & Corwin 1985), SN 1987A (Arnett et al. 1989), SN 1993J (Wheeler & Filippenko 1994), and SN 1991T and SN 1991bg can be mentioned here. Each displayed new and unexpected behavior.

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