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OPTICAL SPECTRA OF SUPERNOVAE

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ABSTRACT

The temporal evolution of the optical spectra of various types of supernovae (SNe) is illustrated, in part to aid observers classifying supernova candidates. Type II SNe are defined by the presence of hydrogen, and they exhibit a very wide variety of photometric and spectroscopic properties. Among hydrogen-deficient SNe (Type I), three subclasses are now known: those whose early-time spectra show strong Si II (Ia), prominent He I (Ib), or neither Si II nor He I (Ic). The late-time spectra of SNe Ia consist of a multitude of blended emission lines of iron-group elements; in sharp contrast, those of SNe Ib and SNe Ic (which are similar to each other) are dominated by several relatively unblended lines of intermediate-mass elements. Although SNe Ia, which result from the thermonuclear runaway of white dwarfs, constitute a rather homogeneous subclass, important variations in their photometric and spectroscopic properties are undeniably present. SNe Ib/Ic probably result from core collapse in massive stars largely stripped of their hydrogen (Ib) and helium (Ic) envelopes, and hence they are physically related to SNe II. Indeed, the progenitors of some SNe II seem to have only a low-mass skin of hydrogen; their spectra gradually evolve to resemble those of SNe Ib. In addition to the two well-known photometric subclasses (linear and plateau) of SNe II, which may exhibit minor spectroscopic differences, there is a new subclass (SNe IIn) distinguished by relatively narrow emission lines with little or no P Cygni absorption component and slowly declining light curves. These objects probably have unusually dense circumstellar gas with which the ejecta interact.

1. INTRODUCTION

The study of supernovae (SNe) has expanded tremendously during the past decade. A major motivation, of course, was provided by SN 1987A, by far

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the most thoroughly observed supernova (SN) in history. Advances in the field have also been driven by technology: The advent of sensitive detectors, especially charge-coupled devices (CCDs), and the proliferation of moderately large telescopes made it possible to obtain excellent photometry and spectroscopy of large numbers of SNe. In addition to their intrinsic interest, SNe are relevant to nucleosynthesis and galactic chemical evolution, the production of neutron stars and black holes, the origin of cosmic rays, the physical state of the interstellar medium, and induced star formation; thus, they have been investigated from a wide range of perspectives. Finally, the enormous potential of SNe as cosmological distance indicators is inspiring many new studies.

This review concentrates primarily on the observed optical spectra of SNe, illustrating the temporal evolution of the major classes and subclasses. When combined with other observations and properly interpreted, such data can reveal the chemical composition of the ejecta, the nature of the progenitors, the explosion mechanisms, and even the distances of SNe. Optical light curves are briefly summarized; it is difficult to entirely decouple discussions of the photometric and spectral evolution of SNe. Details concerning light and color curves can be found in Kirshner (1990), Ford et al (1993), Leibundgut (1994, 1996), Patat et al (1994), Suntzeff (1996), Richmond et al (1996b), and other articles.

Conference proceedings or collections of reviews devoted to many different aspects of SNe (in some cases largely to SN 1987A) include those edited by Wheeler (1980), Rees & Stoneham (1982), Bartel (1985), Danziger (1987), Kafatos & Michalitsianos (1988), Brown (1988), Proust & Couch (1988), Wheeler et al (1990), Petschek (1990), Woosley (1991), Danziger & Kjär (1991), Ray & Velusamy (1991), Audouze et al (1993), Clegg et al (1994), Bludman et al (1995), McCray & Wang (1996), and Ruiz-Lapuente et al (1997). Additional reviews include those of Oke & Searle (1974), Trimble (1982, 1983), Woosley & Weaver (1986), Dopita (1988), Weiler & Sramek (1988), Arnett et al (1989), Imshennik & Nadëzhin (1989), Hillebrandt & Höflich (1989), Wheeler & Harkness (1990), Branch et al (1991), Branch & Tammann (1992), McCray (1993), Chevalier (1981, 1995), and Arnett (1996, especially Chapter 13). Infrared (IR) spectra of SNe are discussed by Meikle et al (1993, 1997) and others. A thorough atlas of International Ultraviolet Explorer (IUE) spectra of SNe, together with some optical spectra, light curves, and many useful references, has been published by Cappellaro et al (1995c). Recently, Wheeler & Benetti (1997) have concisely summarized many of the basic observed properties of SNe.

The most extensive catalogs of SNe are those of the Asiago Observatory (Barbon et al 1989, with an update by van den Bergh 1994) and the Sternberg Astronomical Institute. These are now regularly maintained and available electronically on the World Wide Web (http://athena.pd.astro.it/∼supern/snean.txt and http://www.sai.msu.su/groups/sn/sncat/sn.cat, respectively). The Palomar catalog of SNe (Kowal & Sargent 1971) is no longer updated.

Unless otherwise noted, the optical spectra illustrated here were obtained by the author or his collaborators, primarily with the 3-m Shane reflector at Lick Observatory. They have been shifted to their rest frame; in each case the adopted redshift is listed in the caption. Telluric lines were generally removed, but the spectra were not dereddened. Although the relative spectrophotometry (i.e. the shape of each spectrum) is accurate, the absolute scale is arbitrary. Universal time (UT) dates are used throughout this review. When referring to phase of evolution, the variables t and τ denote time since maximum brightness (usually in the B passband) and time since explosion, respectively.

2. GENERAL OVERVIEW OF SUPERNOVAE

2.1 *Spectra*

Supernovae occur in at least three, and possibly four or more, spectroscopically distinct varieties. The two main classes, Types I and II, were firmly established by Minkowski (1941, but see Popper 1937). Type I SNe are defined by the absence of obvious hydrogen in their optical spectra, except for possible contamination from superposed H II regions. SNe II all prominently exhibit hydrogen in their spectra, yet the strength and profile of the Hα line vary widely among these objects. Until recently, most spectra of SNe have been obtained near the epoch of maximum brightness, but in principle the classification can be made at any time, as long as the spectrum is of sufficiently high quality. Only occasionally (Section 5.5) do SNe metamorphose from one type to another, suggesting the use of hybrid designations.

The early-time ($t \approx 1$ week) spectra of SNe are illustrated in Figure 1. The lines are broad owing to the high velocities of the ejecta, and most of them have P Cygni profiles formed by resonant scattering above the photosphere. SNe Ia are characterized by a deep absorption trough around 6150 Å produced by blueshifted Si II $\lambda\lambda$6347, 6371 (collectively called λ6355). Members of the Ib and Ic subclasses do not show this line. The presence of moderately strong optical He I lines, especially He I λ5876, distinguishes SNe Ib from SNe Ic (Wheeler & Harkness 1986, Harkness & Wheeler 1990).

The late-time ($t \gtrsim 4$ months) optical spectra of SNe provide additional constraints on the classification scheme (Figure 2). SNe Ia show blends of dozens of Fe emission lines, mixed with some Co lines. SNe Ib and Ic, on the other hand, have relatively unblended emission lines of intermediate-mass elements such as O and Ca. Emission lines in SNe Ib are narrower (Filippenko et al 1995b) and perhaps stronger (Wheeler 1990) than those in SNe Ic, but these

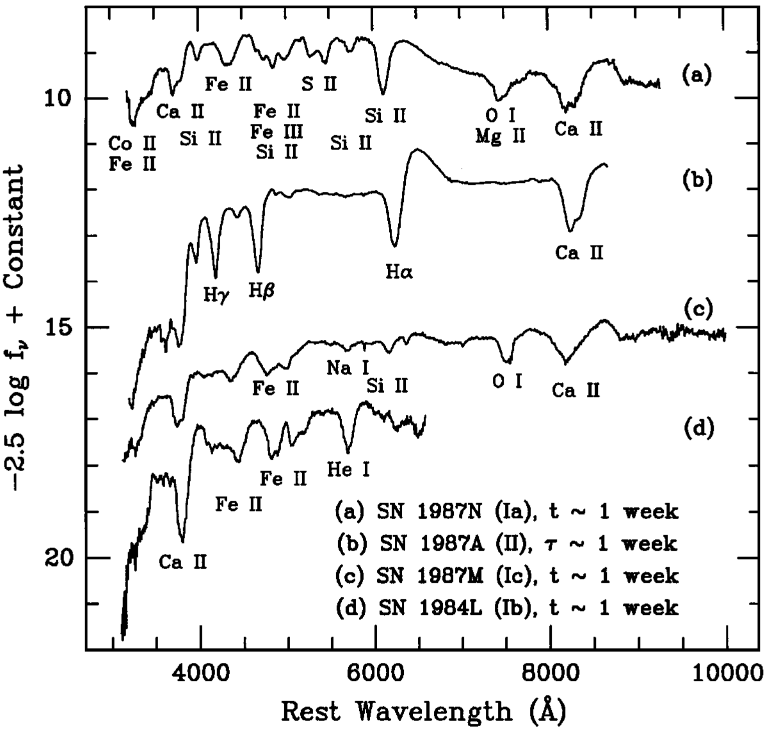

Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables t and τ represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

conclusions are based on the few existing late-time spectra of SNe Ib, and no other possibly significant differences have yet been found. At this phase, SNe II are dominated by the strong Hα emission line; in other respects, most of them spectroscopically resemble SNe Ib and Ic, but the emission lines are even narrower and weaker (Filippenko 1988). The late-time spectra of SNe II show substantial heterogeneity, as do the early-time spectra.

At ultraviolet (UV) wavelengths, all SNe I exhibit a very prominent early-time deficit relative to the blackbody fit at optical wavelengths (e.g. Panagia 1987). This is due to line blanketing by multitudes of transitions, primarily those of Fe II and Co II (Branch & Venkatakrishna 1986). The spectra of SNe Ia (but not of SNe Ib/Ic) also appear depressed at IR wavelengths (Meikle

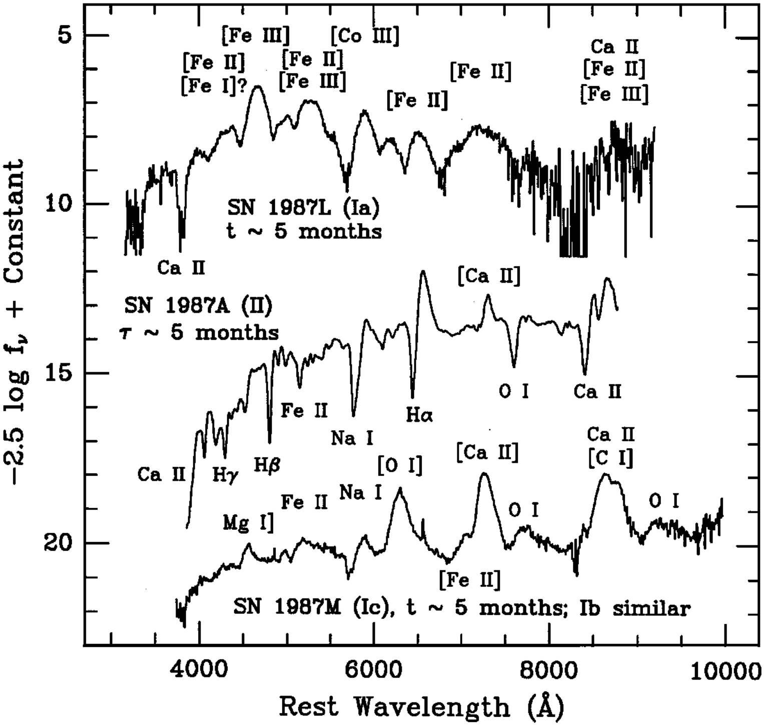

Figure 2 Spectra of SNe, showing late-time distinctions between various types and subtypes. Notation is the same as in Figure 1. The parent galaxy of SN 1987L is NGC 2336 ($cz = 2206$ km s^{-1}); others are listed in the caption of Figure 1. At even later phases, SN 1987A was dominated by strong emission lines of Hα, [O I], [Ca II], and the Ca II near-IR triplet, with only a weak continuum.

et al 1997). The early-time spectra of most SNe II, in contrast, approximate the single-temperature Planck function from UV through IR wavelengths, with occasionally even a slight UV excess. SN 1987A was an exception: The earliest IUE spectra showed a strong UV deficit relative to the blackbody curve defined at optical wavelengths (Danziger et al 1987), as in SNe I.

2.2 *Light Curves*

Some representative optical light curves of SNe are shown by Minkowski (1964); much more complete atlases of SNe I and SNe II are given by Leibundgut et al (1991c) and Patat et al (1993), respectively. The most obvious conclusion is that to first order, the light curves of SNe I are all broadly similar, whereas those of SNe II exhibit much dispersion.

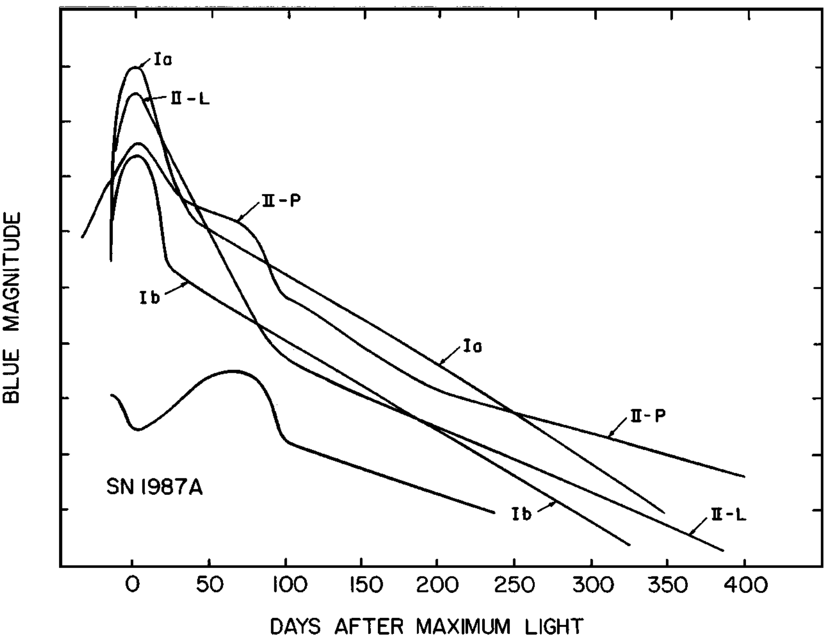

Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous. From Wheeler 1990; reproduced with permission.

Despite their bewildering variety, the majority of early-time light curves of SNe II ($t \lesssim 100$ days) can be usefully subdivided into two relatively distinct subclasses (Barbon et al 1979, Doggett & Branch 1985). The light curves of SNe II-L ("linear") generally resemble those of SNe I, whereas SNe II-P ("plateau") remain within $\sim$1 mag of maximum brightness for an extended period (Figure 3). The degree to which there is a continuity between SNe II-L and SNe II-P is still debated, and other possible classification schemes are being considered (Patat et al 1994). The plateau of SN 1992H, for example, was somewhat shorter than usual and declined with time in the VRI passbands, and it was barely visible or nonexistent in B and U, leading Clocchiatti et al (1996a) to call this a hybrid object.

The peak absolute magnitudes of SNe II-P show a very wide dispersion (Schmitz & Gaskell 1988, Young & Branch 1989), almost certainly due to differences in the radii of the progenitor stars. Most SNe II-L, on the other hand, have a nearly uniform peak absolute magnitude (Young & Branch 1989, Gaskell 1992), ~2.5 mag fainter than SNe Ia, although a few exceptionally luminous SNe II-L (SN 1979C, and to a lesser extent SN 1980K) are known. At late times ($t \gtrsim 150$ days), the light curves of most SNe II resemble each other, both in shape and absolute flux (Turatto et al 1990, Patat et al 1994). The decline rate is close to that expected from the decay of Co^{56} to Fe^{56} (0.98 mag/100 days), especially in V.

The light curve of SN 1987A (Figure 3), although unusual, was generically related to those of SNe II-P; the initial peak was low because the progenitor was a blue supergiant, much smaller than a red supergiant (Arnett et al 1989 and references therein). Additional objects of a possibly similar nature are SN 1909A (Young & Branch 1988) and SNe 1923A, 1948B, and 1965L (Schmitz & Gaskell 1988). Some SNe II decline very slowly at early times (Section 5.4), probably because of energy radiated during the interaction of the ejecta with circumstellar gas (e.g. SN 1987F, Chugai 1991; SN 1988Z, Turatto et al 1993b, Chugai & Danziger 1994); they do not fit into the two main photometric subclasses. Indeed, they appear to constitute a subclass that is also spectroscopically distinct (SN IIn; Section 5.4).

Barbon et al (1973, their Figure 1) illustrate the B-band light curves of 38 SNe I on a single plot, after having adjusted them in both coordinates to minimize the dispersion. There is considerable scatter, some of which is due to intrinsic differences among SNe Ia (Section 3.3). Moreover, three SNe now known to have been SNe Ib (1962L, 1964L, 1966J), as well as some number of unrecognized SNe Ib/Ic, were included in this compilation, yet their light curves are not identical to those of SNe Ia. (Note that the archaic "SNe Ia" and "SNe Ib" of Barbon et al, defined according to photometric properties, should not be confused with the modern, spectroscopic designations.) SNe Ic 1987M and 1994I, for example, declined markedly faster than SNe Ia (Filippenko et al 1990, Richmond et al 1996b), whereas the decline rate of the few SNe Ib that have been studied appears to be slower than that of SNe Ia (Schlegel & Kirshner 1989, Kirshner 1990). Clocchiatti & Wheeler (1997) recently found that the light curves of SNe Ic cluster into two different categories: Some fall more slowly than SNe Ia (like SNe Ib), and others more rapidly, even though they have nearly identical spectra. This serves as an important reminder that light curves can provide physical diagnostics not available from spectra alone.

It is appropriate at this point to mention Zwicky's (1965) SN Types III, IV, and V, all of which had peculiar light curves. Each of these classes has only a few known examples, and in all cases their spectra showed hydrogen. As stated by Oke & Searle (1974) and Doggett & Branch (1985), they should therefore be considered as SNe II (or peculiar SNe II), at least until additional objects that have similar characteristics are found and examined in detail. SN 1961V in NGC 1058 (Type V) had the most bizarre light curve ever recorded. The less luminous SN 1954J, also known as Variable 12 in NGC 2403, had a light curve shape similar to that of SN 1961V; see Humphreys & Davidson (1994). SNe V may not even be genuine SNe, a conclusion reached by Goodrich et al (1989) and Filippenko et al (1995a) for the specific case of SN 1961V; rather, they may be super-outbursts of luminous blue variables such as η Carinae.

2.3 *Environments and Progenitors*

The locations at which SNe occur provide important clues to their nature and to the mass of their progenitor stars. SNe II, Ib, and Ic have never been seen in elliptical galaxies and rarely if ever in S0 galaxies. They are generally in or near spiral arms and H II regions (Huang 1987, Porter & Filippenko 1987, Van Dyk 1992, Van Dyk et al 1996a), implying that their progenitors must have started their lives as massive stars ($\gtrsim$8–10 $M_\odot$). SNe Ia, on the other hand, occur in all types of galaxies, including ellipticals, and in spirals there is no strong preference for spiral arms (Maza & van den Bergh 1976, Van Dyk 1992, McMillan & Ciardullo 1996; but see Bartunov et al 1994b). Because SNe Ia occur most frequently in spiral galaxies, with the rate per unit K-band (2.2 μm) luminosity increasing from early to late Hubble types (Della Valle & Livio 1994), the majority of SNe Ia probably come from intermediate-age ($\sim$0.1–0.5 billion years), moderately massive stars (4–7 $M_\odot$); see Oemler & Tinsley (1979) for an interesting early discussion.

The progenitors of SNe Ia are carbon-oxygen white dwarfs that accrete matter from a companion star and undergo thermonuclear runaway (Nomoto et al 1984, Woosley & Weaver 1986, and references therein). Although the white dwarfs probably reach the Chandrasekhar limit prior to exploding, this is not yet certain (Woosley et al 1994, Livne & Arnett 1995, but see Höflich et al 1996a). SNe II are thought to arise from evolved, massive progenitors (initial mass $\gtrsim$ 8–10 $M_\odot$) that suffer core collapse (generally iron) and subsequently rebound (e.g. Arnett et al 1989), leaving a neutron star or perhaps in some cases a black hole (Brown & Bethe 1994). Most workers now believe that SNe Ib/Ic are produced by the same mechanism as SNe II, except that the progenitors were stripped of their hydrogen (SN Ib) and possibly helium (SN Ic) envelopes prior to exploding, either via mass transfer to companion stars (Nomoto et al 1994, Woosley et al 1995) or through winds (Woosley et al 1993, Swartz et al 1993b, and references therein). White dwarf models have been discussed (e.g. Branch & Nomoto 1986) but are implausible.

3. TYPE Ia SUPERNOVAE

3.1 *Spectral Evolution*

The first thorough long-term set of spectra of a SN Ia was that of SN 1937C, obtained photographically by Minkowski (1939), with an intensity calibration provided by Greenstein & Minkowski (1973). The use of linear detectors having high quantum efficiency (especially CCDs) led to the publication of better sequences of spectra of "normal SNe Ia" (Section 3.3), specifically those of SN 1972E (Kirshner et al 1973, Kirshner & Oke 1975), SN 1981B (Branch et al 1983), SN 1989B (Barbon et al 1990, Wells et al 1994), and SN 1994D (Meikle et al 1996, Patat et al 1996, Filippenko 1997a). Wells et al (1994) discuss in some detail the temporal changes in their densely sampled spectra of SN 1989B. A representative set of spectra of SN 1994D is illustrated in Figure 4.

The early-time spectra of SNe Ia exhibit prominent broad peaks and valleys. Extensive computer modeling of the expanding ejecta has resulted in reliable identifications for most features, after decades of uncertainty. In general, at very early times they are attributed to lines of neutral and singly ionized intermediate-mass elements (O, Mg, Si, S, Ca), with some contribution from iron-peak elements (Fe, Co) especially at near-UV wavelengths (Branch et al 1983, 1985, Harkness 1986, 1991, Kirshner et al 1993, Mazzali et al 1993). The strongest features are Si II λ6355 and Ca II H&K $\lambda\lambda$3934, 3968. Convincing evidence for the presence of helium has never been shown, although the results of Meikle et al (1996) are intriguing and warrant further scrutiny.

The relative contribution of iron-group elements quickly increases as the photosphere recedes into the ejecta. By $t \approx 2$ weeks the spectrum is dominated by lines of Fe II, which is consistent with an iron-rich core (Harkness 1991), but some lines of intermediate-mass elements are still present (e.g. Si II, Ca II). Thereafter the spectral changes are more gradual, although forbidden emission lines of Fe (and some Co, most prominent at $\sim$5900 Å) eventually dominate in the nebular phase (Axelrod 1980), which begins roughly one month past maximum brightness. Nevertheless, Ca II remains visible, primarily in absorption (Ca II H&K and the near-IR triplet of $\lambda\lambda$8498, 8542, 8662). Qualitatively, Axelrod (1980) was able to show that the cobalt lines decrease with time in a manner suggestive of radioactive decay. More recently, compelling evidence that the late-time tail of SNe Ia is powered by the decay of radioactive Co^{56} (initially from radioactive Ni^{56}) was found from the temporal changes in the intensity ratio of two relatively unblended [Co III] and [Fe III] emission lines (Kuchner et al 1994; see also Varani et al 1990 for the case of SN 1987A). Also, Spyromilio et al (1992) demonstrated the presence of a large amount (0.4–0.7 $M_\odot$) of iron in the ejecta of SN 1991T. Incidentally, SN 1991T is the only SN Ia to have been observed spectroscopically more than two years past maximum, but the data were dominated by an echo produced by foreground dust reflecting the near-maximum spectrum (Schmidt et al 1994c).

Early-time photospheric expansion velocities, determined by measuring the positions of Doppler-shifted absorption minima in the P Cygni profiles of strong, fairly unblended lines such as Si II λ6355, are typically $\gtrsim$10,000 km s^{-1}

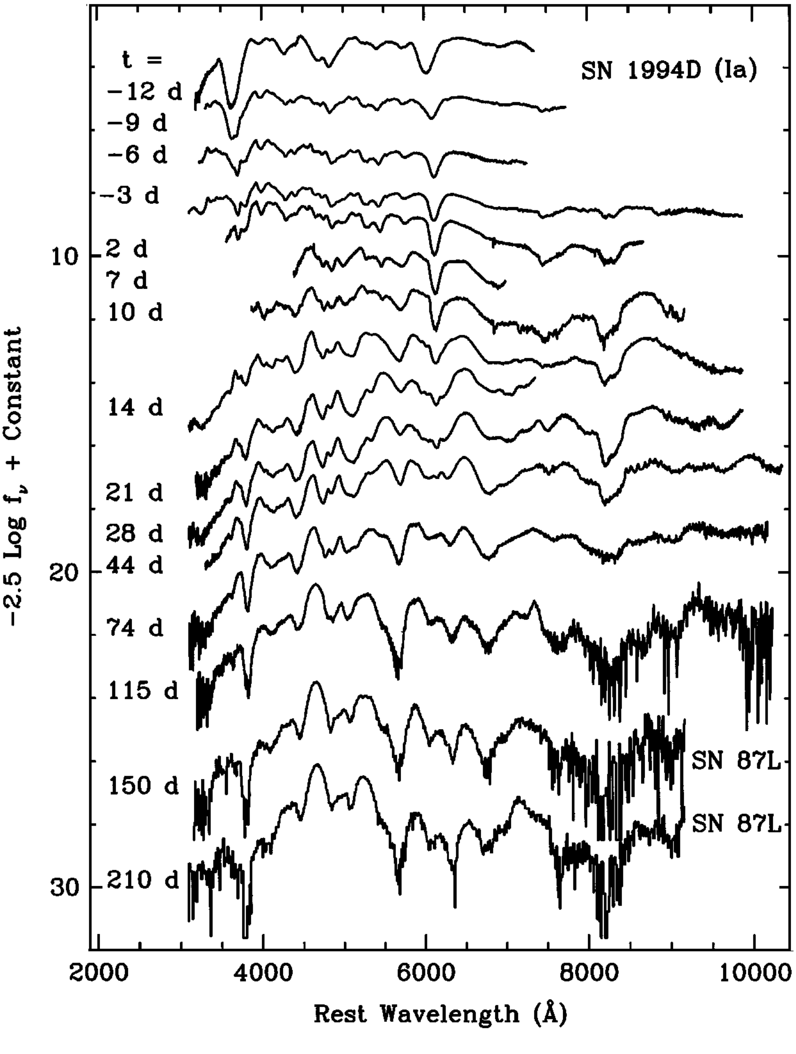

Figure 4 Montage of spectra of SN Ia 1994D in NGC 4526 ($cz = 850$ km s^{-1}), based on data from Patat et al (1996; reproduced with permission) and Filippenko (1997a). Epochs (days) are given relative to maximum B brightness (March 20.5, 1994). The last two spectra are of the similar SN Ia 1987L in NGC 2336.

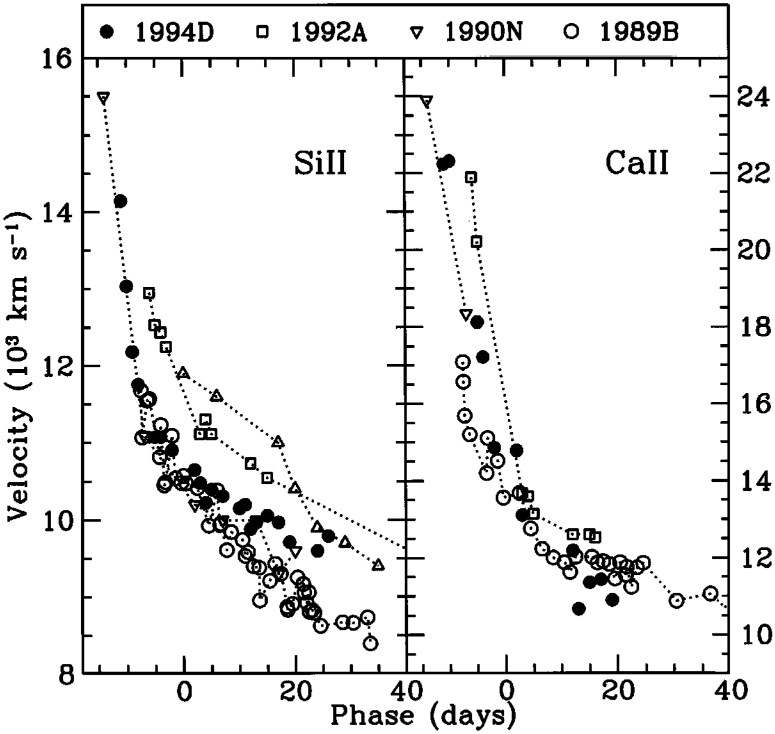

Figure 5 Evolution of the expansion velocity as deduced from the minima of the Si II λ6355 (*left panel*) and Ca II H&K (*right panel*) absorption troughs for SNe Ia 1994D, 1992A, 1990N, 1989B, and 1981B. From Patat et al (1996); reproduced with permission.

(Pskovskii 1977, Branch 1981). Different lines do not have identical velocities: for example, Si II (10,000–12,000 km s^{-1}) and Ca II H&K (13,000–15,000 km s^{-1}) at maximum brightness. Initially the velocity obtained from the Si II and Ca II H&K lines decreases rapidly with time, as shown most recently by Wells et al (1994) and Patat et al (1996); see Figure 5. Patat et al (1996) note that there is a sudden break in the decline rate around $t = -6$ days, most easily visible in the Si II line (Figure 5).

Note that the broad emission near 6500 Å, which begins to develop around $t = 2$ weeks and remains thereafter with some changes in shape (Figure 4), is not Hα but rather Fe II and later [Fe II]. It is occasionally incorrectly identified as Hα by observers attempting to classify spectra of SN candidates. Similarly, the strong Si II λ6355 line at early times is sometimes attributed to Hα. In both cases, erroneous classifications of Type II are made, especially when uncalibrated spectra are quickly examined at the time of observation.

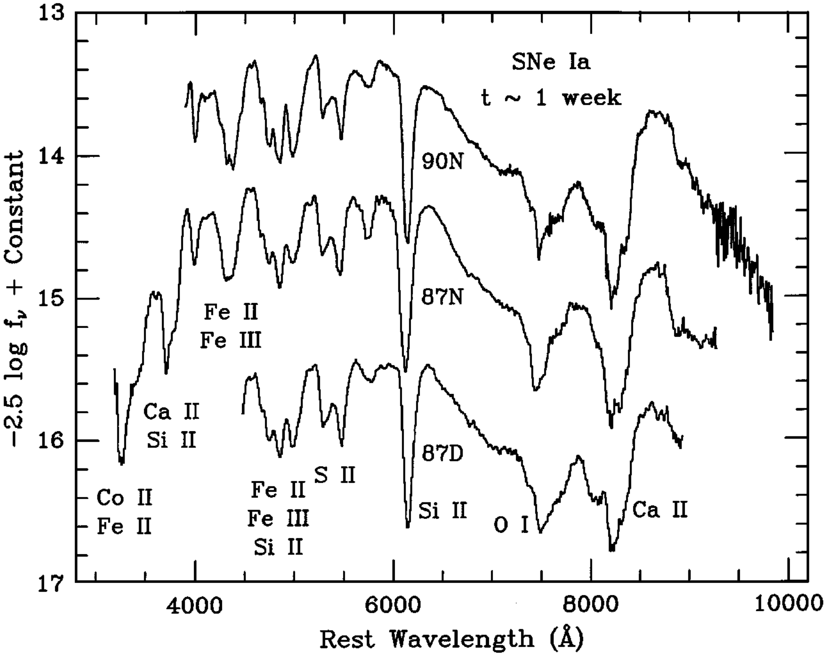

Figure 6 Spectra of SNe Ia about one week past maximum brightness. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1990N (NGC 4639; 970), SN 1987N (NGC 7606; 2171), and SN 1987D (MCG+00-32-01; 2227).

3.2 *Homogeneity*

It was noticed long ago that the optical spectra of SNe Ia are usually quite homogeneous, if care is taken to compare objects at similar times relative to maximum brightness (Oke & Searle 1974, and references therein). One can even deduce a fairly accurate age of a "normal" SN Ia at the time of observation by comparison of its spectrum with a series of template spectra, such as those of SNe 1937C, 1972E, 1981B, 1989B, and 1994D mentioned above. A good example of this homogeneity is provided by spectra (Figure 6) of SN 1987D, SN 1987N, and SN 1990N, each about one week after maximum brightness. Especially impressive are the small "notches" visible in all three spectra near 4550 Å, 4650 Å, and 5150 Å.

The optical light curve shapes of many SNe Ia also closely resemble each other (e.g. Hamuy et al 1991). By examining a large quantity of data, Leibundgut (1988) constructed "template" light curves in several bandpasses. It is striking that the B and V light curves of SN 1990N (Leibundgut et al 1991a), discovered two weeks before maximum brightness, very closely match the previously determined templates.

Branch & Miller (1993), Vaughan et al (1995), and others have quantified the dispersion in the peak absolute magnitude of unreddened SNe Ia. By including only those SNe Ia whose B–V color at maximum brightness is within the range −0.25 to 0.25 mag, Vaughan et al found that $<M_B> = -18.54 \pm 0.06 + 5\log(H_0/85)$ mag and $<M_V> = -18.59 \pm 0.06 + 5\log(H_0/85)$ mag, where the units of H_0 are kilometers per second per megaparsec. Much of the measured dispersion (only 0.30 mag in both cases) may be due to observational errors, incorrect relative distances, and residual reddening; the intrinsic dispersion is certainly smaller.

3.3 *Heterogeneity*

Nevertheless, careful inspection of high-quality data demonstrates that differences among SNe Ia do indeed exist. In Figure 6, for example, the depths of the features near 5750 Å and 8050 Å differ. Moreover, the ejecta of SNe Ia do not always have the same velocity at a given phase (Branch 1987, Branch et al 1988; see also Figures 5 and 6). Remarkably, the smallest ejection velocities are generally found among SNe Ia in elliptical galaxies (Filippenko 1989b, Branch & van den Bergh 1993). A spectroscopic distinction between SNe Ia in spiral and elliptical galaxies clearly indicates that there are real physical differences among SNe Ia; the dissimilar ejection velocities cannot be a consequence of viewing an asymmetric explosion from different angles. Also, after many tenuous suggestions (e.g. Barbon et al 1973, Rust 1974, Pskovskii 1977, 1984, Branch 1981), variations in the light curve shapes among SNe Ia have finally been confirmed beyond doubt and shown to be correlated with luminosity: Intrinsically bright SNe Ia rise and decline more slowly than dim ones (Phillips 1993, Hamuy et al 1995, 1996a, Riess et al 1995a, 1996). The most luminous SNe Ia seem to occur in young stellar populations (Hamuy et al 1995, Branch et al 1996), which is an important result.

Spectroscopic and photometric peculiarities have been noted with increasing frequency in well-observed SNe Ia during the past decade. One of the best examples is SN 1986G: Phillips et al (1987) and Cristiani et al (1992) observed anomalies in the optical spectra as well as a rapid postmaximum decline in the UBV bands, Frogel et al (1987) reported clearly discrepant IR (JHK) light curves, and the early-time UV spectrum was unusual (Panagia & Gilmozzi 1991). Another interesting object, SN 1990N (Leibundgut et al 1991a, Phillips et al 1992, Mazzali et al 1993), had significantly weaker Si II absorption (at 6150 Å) at $t = -1$ week than did the normal SNe Ia 1989B and 1994D (Figure 7), but its postmaximum evolution was typical. A striking case is SN 1991T; its premaximum spectrum did not exhibit Si II or Ca II

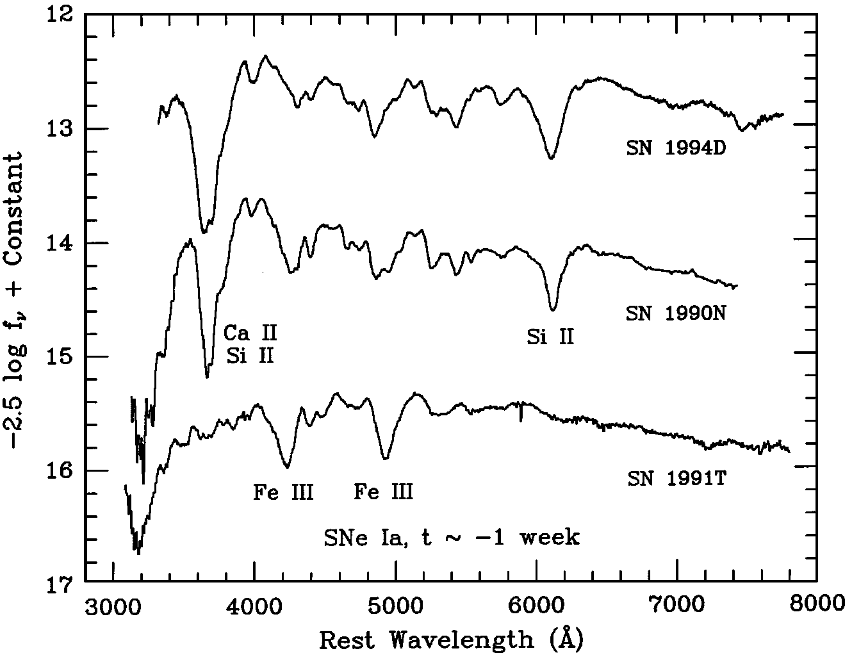

Figure 7 Spectra of SNe Ia about one week before maximum brightness. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1994D (NGC 4526; 850), SN 1990N (NGC 4639; 970), and SN 1991T (NGC 4527; 1740).

absorption lines at all (Figure 7), yet two months past maximum the spectrum was nearly indistinguishable from that of a classical SN Ia (Filippenko et al 1992b, Ruiz-Lapuente et al 1992, Phillips et al 1992, Jeffery et al 1992, Mazzali et al 1995). Superior photometry reported by Phillips et al (1992) shows that the light curves of SN 1991T were slightly broader than the SN Ia template curves, and the object was probably somewhat more luminous than average at maximum (Filippenko et al 1992b, Phillips 1993, Riess et al 1996). Spectroscopically similar objects were subsequently identified by Filippenko & Leonard (1995; SN 1995ac) and by Garnavich et al (1995b; SN 1995bd).

SN 1991bg, in the E1 galaxy NGC 4374, is the reigning champion of well-observed peculiar SNe Ia (Filippenko et al 1992a, Leibundgut et al 1993, Turatto et al 1996, Mazzali et al 1997). At maximum brightness, SN 1991bg was subluminous by 1.6 mag in V and 2.5 mag in B, compared with normal SNe Ia. The colors were unusually red at maximum, but the object was not significantly reddened by dust; indeed, at late times the object may have been slightly bluer than normal SNe Ia (Leibundgut et al 1993). The decline from maximum was certainly quite steep; Filippenko et al (1992a) measured an initial linear V fading of 0.10 mag day^{-1}, rather than the typical value of 0.06 mag day^{-1} for SNe Ia, and a late-time decline of 0.034 mag day^{-1}, rather than 0.026 mag day^{-1}. Also, the "knee" in the V light curve of SN 1991bg occurred only ~20 days past maximum, in contrast to the usual value of ~35 days. Unlike the case in normal SNe Ia, the I-band light curve did not exhibit a secondary maximum, and the R-band light curve showed no sign of a plateau. Furthermore, the spectrum of SN 1991bg at maximum had a deep trough around 4200 Å produced by Ti II (Filippenko et al 1992a); lines of Ti II and other intermediate-mass elements were present elsewhere in the spectrum as well, whereas Fe II was weak or absent. The expansion velocity (~10,000 km s^{-1}) was slightly lower than average (11,000–13,000 km s^{-1}) for luminous SNe Ia. A spectrum obtained three weeks past maximum showed a relatively narrow absorption line attributed to Na I D, as well as the emergence of forbidden emission lines; apparently the nebular phase began very early in SN 1991bg. Three months past maximum the [Ca II] $\lambda\lambda$7291, 7324 blend began dominating the spectrum.

Although "normal" SNe Ia (defined by objects such as SNe 1937C, 1972E, 1981B, 1989B, and 1994D) constitute a majority ($\gtrsim$80%) of SNe Ia observed thus far (Branch et al 1993), very subluminous and peculiar SNe Ia like SN 1991bg might be intrinsically as common per unit volume but are more difficult to find (e.g. Schaefer 1996). The second known example is SN 1992K (Hamuy et al 1994), whose luminosity, spectral characteristics, light curves, and color curves were nearly identical to those of SN 1991bg. Note that the host galaxy of SN 1992K is a spiral, whereas that of SN 1991bg is an elliptical, though SN 1992K may have been associated with the older bulge population. Yet another probable member of this subclass is SN 1991F in the lenticular galaxy NGC 3458 (Gómez & López 1995): Its late-time spectrum closely resembled that of SN 1991bg, but its photometric properties are unknown. In all cases where the requisite data have been obtained, the subluminous objects are intrinsically red compared with most normal SNe Ia (Hamuy et al 1995, Vaughan et al 1995).

Maza et al (1994) present a striking example of the photometric heterogeneity of SNe Ia. As part of the Calán/Tololo search for SNe, they discovered two SNe Ia at redshift $z = 0.02$, presumably at nearly the same distance because the peculiar velocities of their host galaxies are likely to be small relative to the Hubble flow. SN 1992bc was 0.69-mag brighter than SN 1992bo in B; in addition, its light curves declined more slowly than those of SN 1992bo, and in fact closely resembled those of the overluminous SN 1991T (Phillips et al 1992, Phillips 1993). Differences in the shapes of high-quality CCD light curves of numerous SNe Ia are illustrated by Riess (1996) and Hamuy et al (1996c).

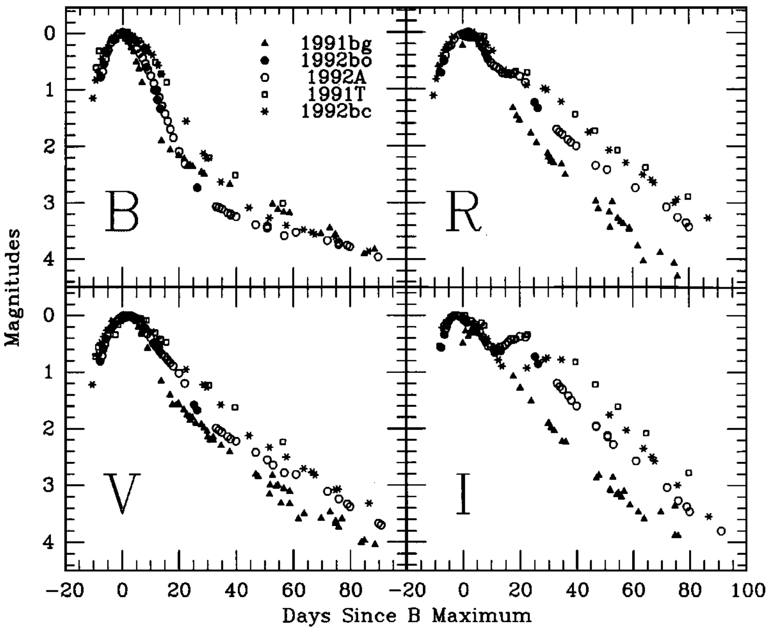

Figure 8 BV (*left panels*) and RI (*right panels*) evolution of bright SNe Ia. From Suntzeff (1996); reproduced with permission.

The photometric heterogeneity among extreme examples of SNe Ia is perhaps best demonstrated by Suntzeff (1996) with five objects that have excellent BVRI light curves, all scaled to the same maximum brightness (Figure 8). The differences in decline rates at early times are largest in B, followed by V; they are relatively minor at R and I, except for those of SN 1991bg. At late times, however, the R and I light curves exhibit more scatter than the B and V curves. Two months past maximum, for example, SN 1991T and SN 1991bg differ by 1.3 mag in R (but very little in B) after normalizing to the same peak. Suntzeff (1996) goes on to show the difference in bolometric (near-UV through near-IR) luminosity of four SNe Ia as a function of time. At maximum brightness, SN 1991T was a factor of 5 more luminous than SN 1991bg, and this grew to a factor of 9 by one month past maximum.

3.4 *Cosmological Uses of SNe Ia*

Despite not being truly “standard” candles (cf Branch & Tammann 1992, and references therein), SNe Ia are still exceptionally useful for cosmological studies (e.g. Riess et al 1995a,b, 1996, Hamuy et al 1995, 1996a,b, Perlmutter et al

1995, 1997, Goobar & Perlmutter 1995, Leibundgut et al 1996, Goldhaber et al 1997, Filippenko 1997b, Kim et al 1997, Schmidt 1997). The key point is that luminosity correlates strongly with light curve shape; given enough high-quality observations, the luminosity of each object can therefore be calibrated. Even the extinction can be determined reliably from observations through several filters (Riess et al 1996), obviating the need to use other, much more uncertain methods such as those based on the strength of the Na I D interstellar absorption lines (e.g. Richmond et al 1994).

There are additional, potentially tight correlations that could enable the peak luminosity of individual SNe Ia to be calibrated even more accurately. Fisher et al (1995) found that the velocity of the red edge of the Ca II H&K absorption line at $t \gtrsim 60$ days in spectra of SNe Ia correlates reasonably well with absolute visual magnitude. Nugent et al (1995) discuss other spectral trends and begin to explore their physical basis. For example, the ratio of the Si II absorption line at 5750 Å to that at 6150 Å increases with decreasing luminosity, as does the ratio of the two peaks on either side of the Ca II H&K absorption trough. The latter could be especially useful when classifying high-redshift SNe Ia. Similarly, Branch et al (1996) found that the U–B color at maximum brightness correlates with absolute magnitude; intrinsically luminous SNe Ia generally exhibit the largest UV excess. Further work is required to see whether at least two independent methods yield the same corrections (within the uncertainties) to the derived peak luminosities of SNe Ia.

3.5 *Hydrogen in Spectra of SNe Ia*

The presence or absence of circumstellar material can shed light on the nature and evolution of SN Ia progenitors, as discussed by Branch et al (1995, and references therein). One way in which this gas can reveal itself is through transient, narrow Hα emission or absorption lines in early-time spectra of SNe Ia. Branch et al (1983), for instance, gave tentative evidence for a weak, narrow Hα emission line in a spectrum of SN 1981B obtained six days after maximum brightness, but Cumming et al (1996) showed that this interpretation is unlikely to be correct. Similarly, Polcaro & Viotti (1991) claimed to have detected Hα absorption in a spectrum of SN 1990M obtained four days after maximum brightness, but Della Valle et al (1996) argued that this was probably an artifact of the reduction procedure.

Calculations by Cumming et al (1996) indicate that circumstellar emission in Hα will drop rapidly after explosion; detection is not possible unless very early observations are made. Sensitive high-resolution spectroscopy is starting to set useful limits on Hα absorption or emission and in turn on the amount of circumstellar hydrogen around SN Ia progenitors. Cumming et al (1996) did not detect Hα in a spectrum of SN 1994D obtained at $t = -10$ days; under the assumption of spherical symmetry for the progenitor's wind, they find an upper limit of $\dot{M}_{\odot} \approx 2.5 \times 10^{-5}$ M year^{-1} (Lundqvist & Cumming 1997) if the wind speed is 10 km s^{-1}. Unfortunately, this limit can exclude only the most extreme symbiotic systems as progenitors of SNe Ia. Later (at t $\approx$ 23 days), Ho & Filippenko (1995; see also Filippenko 1997a) used the Keck telescope to carry out a more sensitive search for Hα in SN 1994D, though they did not detect any absorption or emission features (equivalent width 2σ upper limits of $\sim$3 mÅ) within $\pm$100 km s^{-1} of the SN's systemic velocity. Early-time observations at this sensitivity should be able to reveal narrow Hα from nearby SNe Ia, if it is present.

Thus, to date there have been no convincing detections of narrow, transient Hα in early-time spectra of any SNe Ia, though the sample is still very small. (Also, no such helium lines have been reported, but few if any careful searches have been attempted.) Note, however, that weak hydrogen in spectra of SNe Ia, if ever detected, will not necessarily be of circumstellar origin. For example, at the time of explosion the surface of the white dwarf may contain some hydrogen, presumably donated by the secondary star. If so, it should be a broad feature, as it is in the spectra of classical novae (e.g. Williams et al 1994) but much more subtle. In progenitors consisting of main-sequence or subgiant donors (e.g. cataclysmic variables), the ejecta can strip and ablate gas from the secondary star, thereby contaminating the early-time spectrum with hydrogen (Applegate & Terman 1989, Wheeler 1992), but this has never actually been seen.

For certain progenitor models, Hα emission might be expected in the late-time spectra of SNe Ia. Chugai (1986b) predicted that most of the hydrogen-rich material stripped from a red-giant secondary during the explosion is trapped within the ejecta, subsequently expanding at relatively low speeds. Two-dimensional hydrodynamic calculations supported this hypothesis (Livne et al 1992). The hydrogen becomes visible only after the photosphere recedes substantially, and the expected line width is small: Full width at half maximum (FWHM) $\approx$ 2000 km s^{-1}. Such a feature may have been detected in SN 1991bg by Ruiz-Lapuente et al (1993; see also Turatto et al 1996 and Garnavich & Challis 1997), but there are other possible interpretations if it is real (e.g. [Fe II]; Turatto et al 1996).

4. TYPE Ib AND Ic SUPERNOVAE

4.1 *Historical Development*

Bertola (1964) and Bertola et al (1965) noticed that the early-time spectra of some SNe I (specifically SNe 1962L and 1964L) lack the deep 6150-Å absorption trough. For two decades few, if any, new examples of such objects existed, and they were simply labeled as "peculiar SNe I" (SNe Ip). Interest in them was revitalized in the mid-1980s by the studies of several newly discovered SNe Ip by Uomoto & Kirshner (1985), Wheeler & Levreault (1985), Elias et al (1985), and Panagia et al (1986b). Particularly influential (but unpublished) was an optical, UV, and IR investigation of SN 1983N done by Panagia et al (1986a); subsets of these data have been discussed by Panagia (1985) and Gaskell et al (1986), and radio observations were presented by Sramek et al (1984).

As summarized by Porter & Filippenko (1987), SNe Ip seemed to constitute a distinct subclass, characterized by their (*a*) lack of the 6150-Å Si II absorption trough, (*b*) preference for galaxies having Hubble types Sbc or later, (*c*) proximity to H II regions, (*d*) rather low luminosity, typically 1.5-mag fainter than classical SNe I, (*e*) distinct IR light curves having no secondary maximum around one month past primary maximum, (*f*) reddish colors, and (*g*) emission of radio waves within a year past maximum. The subclass was coined "Type Ib" (Elias et al 1985) to distinguish it from normal SNe Ia. At least one of the earliest studies (Wheeler & Levreault 1985) concluded that the explosion mechanism might be more closely related to that of SNe II than to SNe Ia, but this was not yet certain because the spectroscopic appearance of SNe Ib near maximum seemed to resemble that of somewhat older SNe Ia ($t \approx 1$ month).

The serendipitous discovery of SN 1985F (Filippenko & Sargent 1985, 1986) initially compounded the confusion. Its spectrum was dominated by very strong, broad emission lines of neutral and singly ionized species such as [O I] λλ6300, 6364, [Ca II] λλ7291, 7324, the Ca II near-IR triplet, Mg I] λ4571, and Na I D. The strength of the forbidden lines suggested that SN 1985F was an old SN, as did the exponential decline of the derived light curve (Filippenko et al 1986). This was later confirmed by Tsvetkov (1986), whose inspection of prediscovery plates showed that SN 1985F had reached maximum brightness at $B = 12.1$ mag (one of the brightest SNe in many years!) about 260 days prior to discovery. The complete absence of hydrogen led to a formal classification of SN I, although no known spectra of SNe I at any stage of development resembled that of SN 1985F. The dominance of intermediate-mass elements and other factors suggested that SN 1985F was the explosion of a massive star that had rid itself of hydrogen prior to exploding (Filippenko & Sargent 1986, Begelman & Sarazin 1986, Schaeffer et al 1987), somewhat like the progenitor long ago proposed for Cas A by Chevalier (1976). Was this yet another type of SN I, distinct from SNe Ia and SNe Ib?

An important "unification" occurred when Gaskell et al (1986) showed that a spectrum of the Type Ib SN 1983N, obtained eight months past maximum, was very similar to that of SN 1985F at the time of its discovery. Moreover, Kirshner (quoted in Chevalier 1986; see also Schlegel & Kirshner 1989) found that a late-time spectrum of the Type Ib SN 1984L also resembled that of SN 1985F. Thus, SN 1985F was probably a SN Ib discovered long after maximum, and, conversely, SNe Ib eventually turn into objects whose spectra really are vastly different from those of SNe Ia. Interestingly, Chugai (1986a) had, in fact, already suggested that SN 1985F might be a SN Ib discovered long after maximum. Note, however, that there are no early-time spectra of SN 1985F; thus, it may have been a SN IIb (Section 5.5) or perhaps even a SN Ic, although the latter is unlikely given the relatively slow decline of its light curve (Wheeler & Harkness 1990).

The link between SN 1985F and SNe Ib 1983N/1984L, as well as the convincing discovery of He I lines in early-time spectra of the latter (Harkness et al 1987), provided substantial evidence that SNe Ib are a physically separate subclass of SNe I, probably driven by core collapse of an initially massive star (Wheeler & Levreault 1985). Detailed analysis of the nebular spectrum of SN 1985F (Fransson & Chevalier 1989) strongly supported this hypothesis; in their model, the progenitor had initial and final masses of 25 $M_\odot$ and 8 $M_\odot$, respectively, and $\sim$2 $M_\odot$ of oxygen was ejected. Large departures from local thermodynamic equilibrium (LTE) were invoked by Harkness et al (1987) to produce the observed He I lines.

Gradually it became clear that SNe Ib constitute a heterogeneous subclass, with substantial variations in the observed He I strengths in spectra obtained around maximum brightness. Wheeler & Harkness (1986; see also Harkness et al 1987) suggested that SNe Ib should actually be divided into two separate categories: SNe Ib are those showing strong He I absorption lines (especially He I λ5876) in their early-time photospheric spectra, whereas SNe Ic are those in which He I is not easily discernible. However, they modeled SNe Ic in the same physical way as SNe Ib (Wheeler et al 1987) but with different relative concentrations of He and O in the envelope. Although this nomenclature has been adopted by most authors, use of two subtypes (Ib and Ic) might not be observationally warranted. Few objects have been studied in detail; it is possible that a continuum of helium strengths exists among SNe Ib and that He-rich objects are not fundamentally different from He-poor objects in terms of physical origin (Wheeler et al 1987). Clocchiatti & Wheeler (1997), on the other hand, have recently argued that SNe Ib and Ic show a roughly bimodal distribution of He I strengths and that their progenitors may have significantly different evolutionary phases.

The amount of ejected iron in SNe Ib/Ic is not yet clear. If radioactive Ni^{56} powers the optical display, and if SNe Ia produce 0.6 $M_\odot$ of this isotope (Woosley & Weaver 1986), then the corresponding mass for SNe Ib might be only $\sim$0.15 $M_\odot$ because they are roughly four times fainter than SNe Ia (Wheeler & Levreault 1985). Graham et al (1986) proposed the presence of [Fe II] λ1.644 μm emission in a late-time spectrum of SN Ib 1983N, and they calculated an ejected iron mass of 0.3 $M_\odot$, but Oliva (1987) suggested that the proper identification is Si I.

4.2 *SNe Ib: Spectral Evolution*

Genuine helium-rich SNe Ib appear to be rather rare objects. At present, the most complete series of published spectra of a SN Ib is that of Harkness & Wheeler (1990) for SN 1984L, and even this case includes only the first two months past maximum brightness. As shown in Figure 9, there is no strong evidence of hydrogen, and the 6150-Å trough of SNe Ia is weak or absent at all times. Although some of the absorption lines can be attributed to He I in the earliest spectra, other alternatives exist (e.g. Na I D for the feature near 5800 Å). However, the gradual strengthening of blueshifted ($\sim$7500 km s^{-1}) lines corresponding to He I $\lambda\lambda$4471, 5876, 6678, and 7065 makes the helium identification unambiguous a few weeks past maximum brightness (e.g. the spectrum at $t = 20$ days). This differs markedly from the spectral development of SNe Ia (Figure 4).

The seventh spectrum in Figure 9, obtained about two months past maximum brightness, appears to exhibit weak [O I] $\lambda\lambda$6300, 6364 and especially [O I] λ5577, indicating an early onset of the nebular phase. Strong, broad (FWHM $\approx$ 4500 km s^{-1}) lines of [O I] and [Ca II] $\lambda\lambda$7291, 7324 are visible in the spectra of SN 1984L obtained by Schlegel & Kirshner (1989) 13–14 months past maximum, as is somewhat narrower Mg I] λ4571, but the data are noisy. The last plot in Figure 9 instead shows the late-time spectrum ($t \approx 8$ months) of a similar SN Ib, SN 1983N (from Gaskell et al 1986).

Early-time spectra of SN 1983N were presented by Richtler & Sadler (1983), before the SN Ib subclass had been recognized. The blueshifted minimum of the He I λ5876 line corresponds to a photospheric velocity of 18,200 km s^{-1} about 15 days prior to maximum brightness, and 10 days later this decreased to 13,100 km s^{-1} (Wheeler & Harkness 1990). The velocity given by this line was only $\sim$10,000 km s^{-1} at maximum brightness (Harkness et al 1987), further evidence of the retreat of the photosphere into deeper, more slowly moving layers.

4.3 *Type Ic Spectral Evolution*

The first relatively complete set of spectra illustrating the evolution of a SN Ic (Figure 10) was obtained by Filippenko et al (1990). Shortly after it was discovered, SN 1987M showed spectral characteristics typical of SNe Ic. No lines of hydrogen were visible, and the 6150-Å absorption trough was much weaker than in normal SNe Ia. The strongest features were the P Cygni profile of the Ca II near-IR triplet, O I λ7774 absorption, and Ca II H&K absorption. As the object aged, Fe II lines became prominent (e.g. near 4900 Å and 5500 Å). Strong He I lines did not appear, unlike the case in SN 1984L (Figure 9), and this is the basis for identifying SN 1987M as a SN Ic rather than a SN Ib.

Nebular [O I] $\lambda\lambda$6300, 6364 emission first emerged at $t = $1–2 months, considerably earlier than had been expected. The two lines initially had roughly comparable strength, rather than the usual intensity ratio of three to one, because

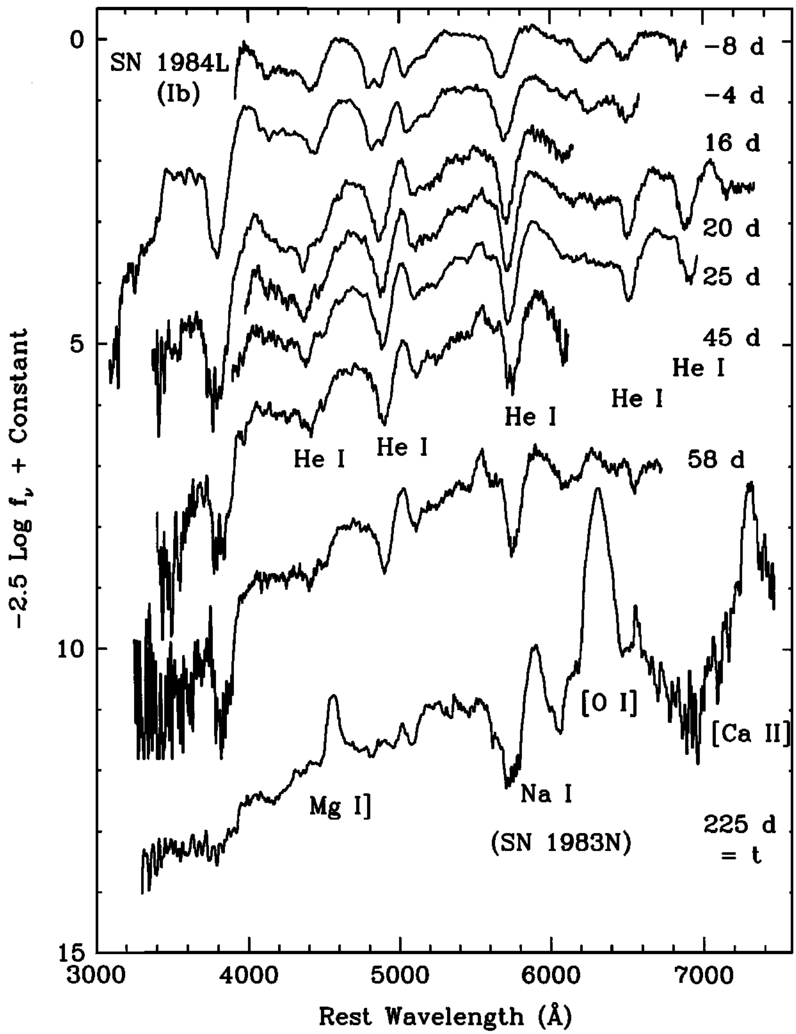

Figure 9 Montage of spectra of SN Ib 1984L in NGC 991 ($cz = 1532$ km s^{-1}), from Harkness et al (1987). The last spectrum is of SN Ib 1983N in NGC 5236 ($cz = 516$ km s^{-1}), from Gaskell et al (1986). Epochs (days) are given relative to maximum B brightness (September 7, 1984, for SN 1984L; July 17, 1983, for SN 1983N). Reproduced with permission.

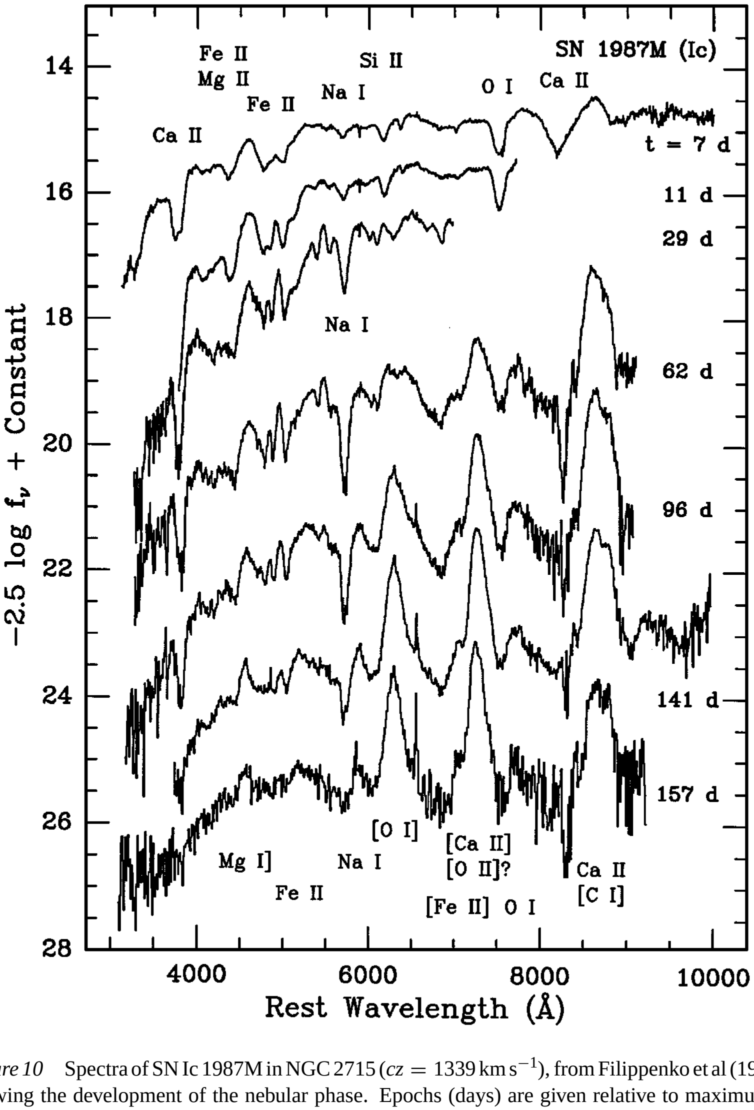

Figure 10 Spectra of SN Ic 1987M in NGC 2715 ($cz = 1339\,\mathrm{km\,s^{-1}}$), from Filippenko et al (1990), showing the development of the nebular phase. Epochs (days) are given relative to maximum B brightness (estimated to be September 21, 1987).

of self-absorption. The intensity ratio of [O I] and [Ca II] emission to the Ca II near-IR triplet increased with time as a consequence of the steadily decreasing electron density. For a while Na I D absorption grew deeper, but after 2–3 months it began to fade. By 5 months past maximum the nebular emission completely dominated the spectrum.

Despite their superficial similarities at early times, the spectra of SNe Ia and SNe Ic evolve in very different manners. The nebular spectra of SNe Ia consist of broad emission-line blends of many forbidden transitions of singly and doubly ionized Fe and Co (Figure 2). SNe Ic (and SNe Ib), on the other hand, are dominated by a few strong, broad, relatively unblended emission lines of neutral oxygen and singly ionized calcium, together with weaker lines of C I, Mg I, Na I, and other intermediate-mass elements (Figure 10).

4.4 *Is There Helium in SNe Ic?*

What evidence do we have that helium is truly absent from the spectra of genuine SNe Ic? Do some (or even most) SNe Ic actually have weak He I lines? [Filippenko (1991b) demonstrated how difficult it can be to distinguish between SNe Ib and SNe Ic, especially if the explosion date is unknown.] If so, what does the helium tell us about the progenitors and their evolutionary histories?

The bright, nearby SN Ic 1994I in NGC 5194 (M51) has begun to shed light on these issues. As shown by Filippenko et al (1995b), strong He I λ10,830 absorption was visible during the first month past maximum brightness (Figure 11). Moreover, the Na I D λ5892 absorption line may have been somewhat contaminated by He I λ5876 (see also Clocchiatti et al 1996c), as evidenced by the weak notch in the blue wing of the Na I D absorption on April 18, 1994. Based on the optical region alone, SN 1994I is clearly a SN Ic; nevertheless, its atmosphere cannot be completely devoid of helium, as is most convincingly demonstrated by the He I λ10,830 line. Clocchiatti et al (1996c) and Clocchiatti & Wheeler (1997) showed that weak optical He I lines appear to be present in several other classical SNe Ic, including SN 1987M (see also Jeffery et al 1991). Indeed, the line at $\sim$5520 Å in the first four spectra of Figure 10 (most easily visible in the third spectrum) is identified as He I λ5876. Thus, the presence of at least some helium is a common property of the progenitors of SNe Ic.

Nomoto et al (1994; see also Iwamoto et al 1994) suggested that the progenitor of SN 1994I was a 2.2-$M_\odot$ C-O core formed as a consequence of two stages of mass transfer in a binary system; during the second stage, helium was lost to the close companion (most likely an O-Ne-Mg white dwarf). Woosley et al (1995), on the other hand, invoked only the first stage of mass transfer, during which the hydrogen envelope is lost to the companion. Depending on the initial mass of the star, the resulting helium star has a mass in the range

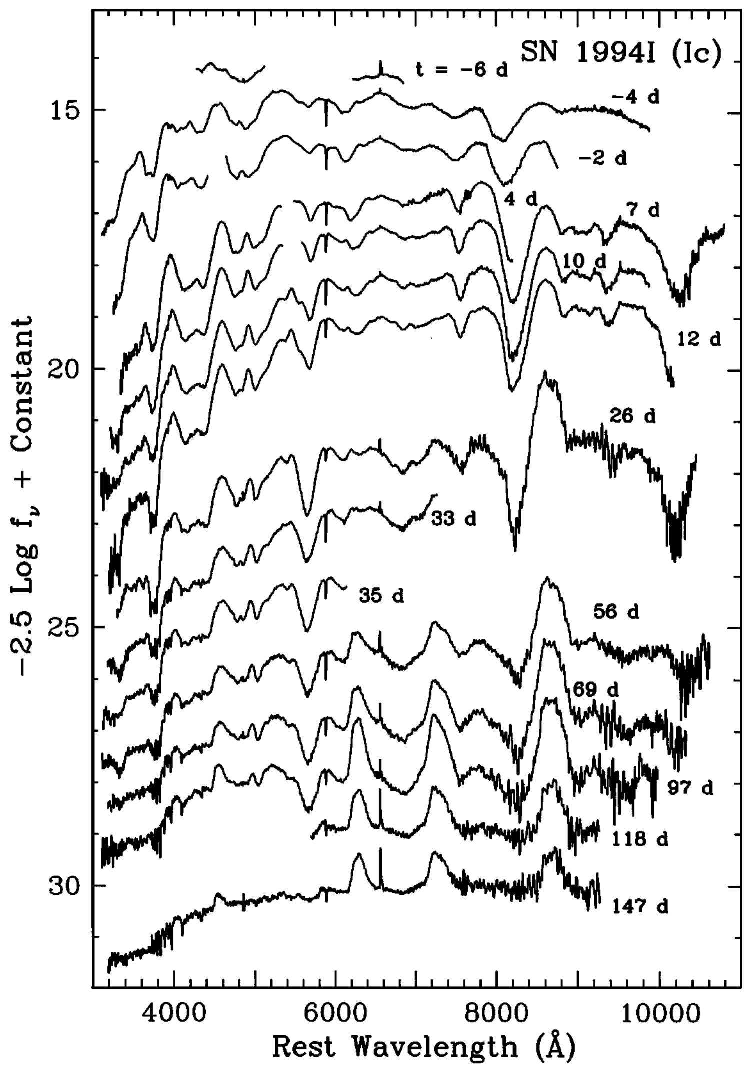

Figure 11 Montage of spectra of SN 1994I in NGC 5194 ($cz = 500$ km s^{-1}), from Filippenko et al (1995b). Epochs (days) are given relative to maximum B brightness (April 8, 1994). The late-time spectra are significantly contaminated by gas and early-type stars in the host galaxy; note the blue continuum, as well as the Balmer absorption and emission lines. Blueshifted He I λ10,830 is prominent at early times, and the transition to the nebular phase is rapid.

4–20 $M_\odot$, but subsequent mass loss through winds is very efficient and makes the final mass of the C-O star always converge to the narrow range 2.26–3.55 $M_\odot$. In both cases, the explosion mechanism was iron core collapse, as in SNe II, but the mass of ejected helium is rather different: $\sim$0.01 $M_\odot$ (Nomoto et al 1994) or 0.1–0.3 $M_\odot$ (Woosley et al 1995).

Baron et al (1996) found no direct evidence for helium (upper limit of $\sim$0.1 $M_\odot$) in a preliminary analysis of the optical spectra of SN 1994I, but they did not include the He I λ10,830 line and non-LTE effects. Naively, if 0.1 $M_\odot$ of helium is moving at 16,500 km s^{-1} (as observed for the He I λ10,830 absorption minimum), the corresponding kinetic energy ($\sim 0.3 \times 10^{51}$ erg) already seems excessive; this may favor the Nomoto et al (1994) model, which requires a factor of 10 less helium. On the other hand, Nomoto et al made a specific prediction about the late-time spectrum of SN 1994I: Emission lines of calcium should exhibit velocities of up to $\sim$10,000 km s^{-1}, and the oxygen lines would be even broader because oxygen is concentrated in the outermost gas layers (Iwamoto et al 1994). This is not the case (Filippenko et al 1995b); despite consisting of the more closely spaced doublet, the [Ca II] line is broader than [O I], and the most rapidly moving oxygen has $v \lesssim 7000$ km s^{-1}.

5. TYPE II SUPERNOVAE

5.1 *Type II-P Supernovae*

Excellent examples of SNe II-P are SN 1969L (Ciatti et al 1971), SN 1986I (Pennypacker et al 1989), SN 1988A (Turatto et al 1993a), SN 1990E (Schmidt et al 1993, Benetti et al 1994), and SN 1991G (Blanton et al 1995). At very early times, the spectrum is nearly featureless and quite blue, indicating a high color temperature ($\gtrsim$10,000 K). Very weak hydrogen Balmer lines and He I λ5876 are often visible. Initially, the widths of the Balmer lines and the blueshifts of their P Cygni absorption minima decrease noticeably in some objects (e.g. SN 1987A; Menzies 1991), as the photosphere quickly recedes to the inner, more slowly moving layers of the homologously expanding ejecta. The temperature rapidly decreases with time, reaching $\sim$5000 K within a few weeks, as expected from the adiabatic expansion and associated cooling of the ejecta. It remains roughly constant at this value during the plateau, while the hydrogen recombination wave moves through the massive ($\sim$10 $M_\odot$) hydrogen ejecta and releases the energy deposited by the shock. At this stage, strong Balmer lines and Ca II H&K with well-developed P Cygni profiles appear, as do weaker lines of Fe II, Sc II, and other iron-group elements. Subsequently, as the light curve drops to the late-time tail, the spectrum gradually takes on a nebular appearance; the continuum fades, but Hα becomes very strong, and prominent emission lines of [O I], [Ca II], and Ca II also appear.

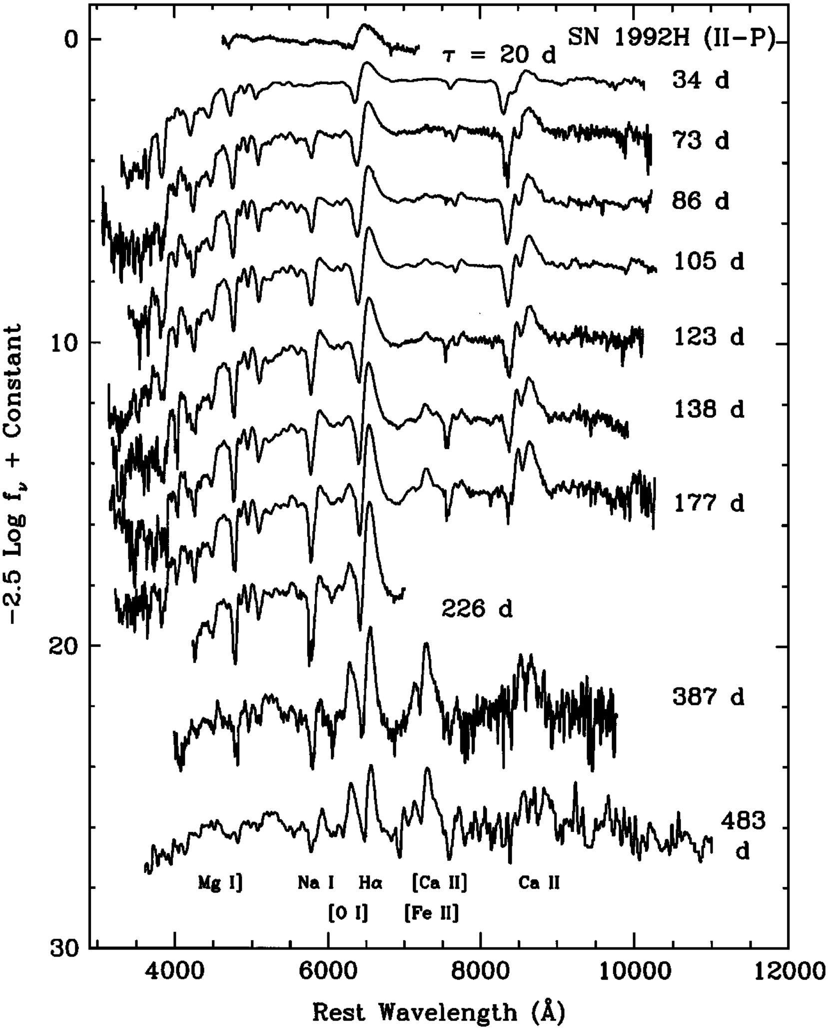

Figure 12 Montage of spectra of SN 1992H in NGC 5377 ($cz = 1793$ km s^{-1}). Epochs (days) are given relative to the estimated date of explosion, February 8, 1992.

This behavior is well illustrated in Figure 12 with SN 1992H (see also Clocchiatti et al 1996a, who estimated the explosion date to be February 8, 1992). Although its V-band plateau ($\tau = 40$–100 days, or perhaps 50–90 days, depending on one's definition) was somewhat shorter than that of the most famous SNe II-P mentioned above and declined slowly with time, SN

1992H can still be considered a SN II-P, and its spectral development was quite typical. Weak He I λ5876 was superposed on a blue continuum on day 20. Hβ absorption was present, but the corresponding component of Hα was weak or absent; Hα emission, on the other hand, was obvious. The Hα absorption line must have developed very rapidly, as it was strong by day 34, and the continuum was redder. The spectrum changed little between days 34 and 123, with the absorption lines gradually growing stronger; Na I D became very prominent, and many lines of singly ionized metals were present. The emergence of weak forbidden emission lines (day 105), most notably [Ca II] $\lambda\lambda$7291, 7324, roughly coincided with the end of the plateau phase; the Ca II near-IR triplet and Na I D emission also became more prominent. By day 138, and certainly by day 177, [O I] λ5577 and [O I] $\lambda\lambda$6300, 6364 were unmistakable. At $\tau \approx 1$ year, when the continuum was faint, the spectrum was dominated by Hα, [Ca II] $\lambda\lambda$7291, 7324, and [O I] $\lambda\lambda$6300, 6364; weaker [Fe II] λ7155, Na D, Mg I] λ4571, the Ca II near-IR triplet, and blends of Fe II lines (especially near 5300 Å) were also present.

SNe II-P are excellent distance indicators, using the "Expanding Photosphere Method" (a variant of the Baade-Wesselink method) described by Kirshner & Kwan (1974); see Schmidt et al (1994a,b), Eastman et al (1996), Filippenko (1997b), and references therein. This technique is independent of the various uncertain rungs in the cosmological distance ladder: It relies only on an accurate measurement of the effective temperature (from the measured colors, with appropriate modeling of deviations from a blackbody spectrum) and the velocity of the photosphere (from the wavelengths of weak absorption lines such as those of Sc II) during the plateau phase. An important check is that the object's derived distance should be independent of time.

5.2 *Supernova 1987A*

SN 1987A, a peculiar variant of SNe II-P, is described extensively in many other reviews (see Section 1); it is mentioned here only briefly. In general, its spectral evolution resembled that of SN 1992H (Figure 12), as can be seen, for example, in Menzies (1991). Jeffery & Branch (1990) presented an analysis that showed that to a considerable extent the evolution of the line spectrum during the first 100 days could be understood on the basis of simplifying assumptions such as resonant-scattering line source functions and LTE line optical depths. One important aspect of the SN 1987A spectrum is that narrow emission lines from the circumstellar ring were present (Wampler & Richichi 1989), and these became dominant at $\tau \gtrsim 3$ years (Wang et al 1996).

Danziger et al (1988) found that around day 530, the peaks of several emission lines (most notably [O I] $\lambda\lambda$6300, 6364) shifted rapidly to bluer wavelengths. This was probably due to the formation of dust in the ejecta (Lucy et al 1991), which is consistent with the nearly simultaneous increase in the decline rate of the optical light curves and the rapid growth of an IR excess. The lines remained blueshifted even in the very late-time spectra obtained with the Hubble Space Telescope ($\tau \approx 2000$ days; Wang et al 1996), which shows that the dust was still present.

The optical spectra of SN 1987A provide considerable evidence for the formation of clumps and mixing of different layers in the ejecta, as had already been deduced from other studies (e.g. X-ray emission; Arnett et al 1989, and references therein). 1. Very early, Hanuschik & Dachs (1987; see also Phillips & Heathcote 1989) drew attention to the "Bochum event," an asymmetry in the Hα and other hydrogen-line profiles. One possibility is that a blob of Ni^{56} was ejected asymmetrically (Chugai 1992, Utrobin et al 1995). 2. Stathakis et al (1991) showed that the [O I] $\lambda\lambda$6300, 6364 profile was serrated in a manner similar to that found for SN 1985F by Filippenko & Sargent (1989), with FWHM typically 80 km s^{-1} for the emission-line peaks. The interpretation is that the [O I]-emitting material is clumpy, probably owing to the formation of Rayleigh-Taylor instabilities at the boundary of the oxygen-rich and helium-rich layers. Chugai (1994a) estimated the mass of clumpy oxygen to be 1.2–1.5 $M_\odot$. 3. Hanuschik et al (1993) showed that the Hα profile exhibited peaks with a somewhat larger velocity scale: FWHM $=$ 160–400 km s^{-1}. Subsequently, Spyromilio et al (1993) demonstrated that at least one of the Hα clumps was also visible in the [Ca II] $\lambda\lambda$7291, 7324 and [Fe II] λ7155 emission lines, directly demonstrating that small-scale mixing of hydrogen and radioactive products occurred in the ejecta.

5.3 *Type II-L Supernovae*

Few SNe II-L have been observed in as much detail as SNe II-P. Figure 13 shows the spectral development of SN 1979C (Branch et al 1981), an unusually luminous member of this subclass (Gaskell 1992). Near maximum brightness the spectrum was very blue and almost featureless, with a slight hint of Hα emission. A week later, Hα emission was more easily discernible, and low-contrast P Cygni profiles of Na I, Hβ, and Fe II appeared. By $t \approx 1$ month, the Hα emission line was very strong but still devoid of an absorption component, while the other features clearly had P Cygni profiles. Strong, broad Hα emission dominated the spectrum at $t \approx 7$ months, and [O I] $\lambda\lambda$6300, 6364 emission was also present.

SN 1980K (Uomoto & Kirshner 1986), another extensively studied (and somewhat overluminous) SN II-L, also did not exhibit an absorption component of Hα at any phase of its development. Several authors (e.g. Wheeler & Harkness 1990, Filippenko 1991a) have speculated that the absence of Hα absorption spectroscopically differentiates SNe II-L from SNe II-P, but the small

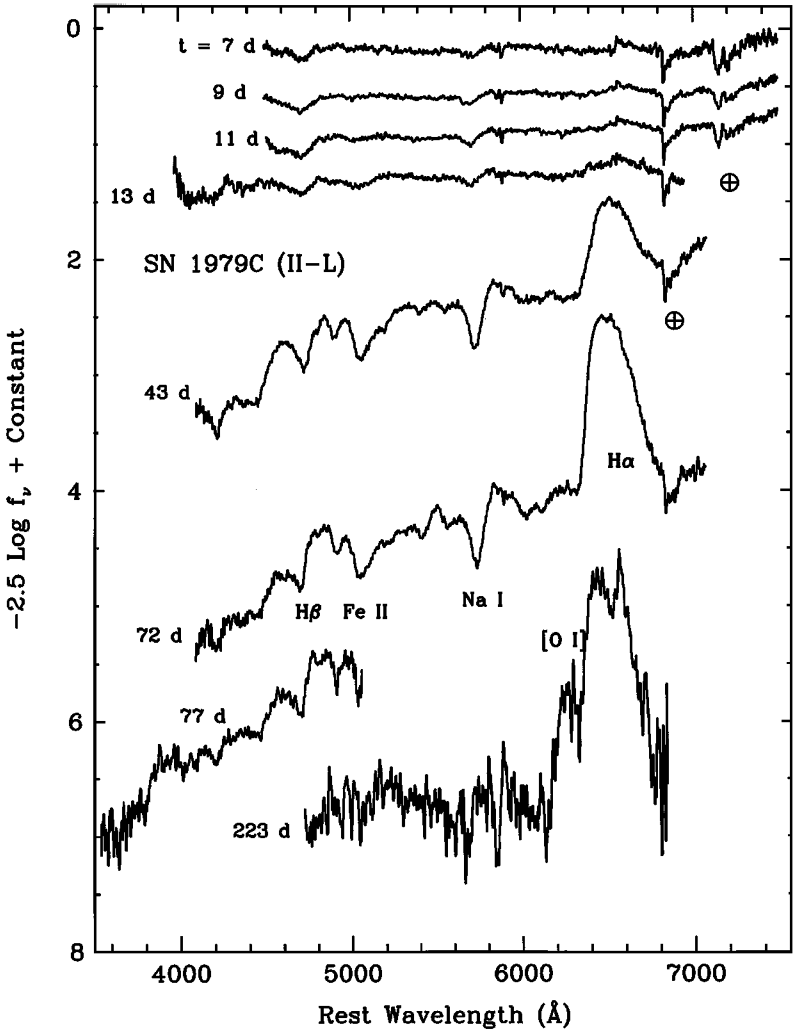

Figure 13 Montage of spectra of SN 1979C in NGC 4321 ($cz = 1571$ km s^{-1}). From Branch et al (1991); reproduced with permission. Epochs (days) are given relative to the date of maximum brightness, April 15, 1979.

size of the sample of well-observed objects precluded definitive conclusions. Recently, Schlegel (1996) collected a somewhat larger set of data and formally proposed that SNe II-L and SNe II-P can be spectroscopically separated in this manner, but it is not yet clear that this is justified. As he himself admitted, the conclusion is based heavily on spectra of SNe 1979C and 1980K, yet these are not necessarily typical SNe II-L. More data are needed to convincingly demonstrate a spectroscopic difference between SNe II-L and SNe II-P.

The progenitors of SNe II-L are generally believed to have relatively low-mass hydrogen envelopes (a few solar masses); otherwise, they would exhibit distinct plateaus, as do SNe II-P. On the other hand, perhaps their envelopes are very extended, or the progenitors have more circumstellar gas than do SNe II-P, and this could give rise to the emission-line dominated spectra (see Section 5.4). They are often radio sources (Sramek & Weiler 1990); moreover, Fransson (1982, 1984) suggested that the UV excess (at $\lambda \lesssim 1600$ Å) seen in SNe 1979C and 1980K is produced by inverse Compton scattering of photospheric radiation by high-speed electrons in shock-heated ($T \approx 10^9$ K) circumstellar material. Finally, the light curves of some SNe II-L reveal an extra source of energy: After declining exponentially for several years after outburst, the Hα flux of SN 1980K reached a steady level, showing little if any decline thereafter (Uomoto & Kirshner 1986, Leibundgut et al 1991b). The excess almost certainly came from the kinetic energy of the ejecta that was thermalized and radiated owing to an interaction with circumstellar matter (Chevalier 1990, Leibundgut 1994, and references therein). Note that Swartz et al (1991) explored the possibility that SNe II-L may result from electron-capture–induced collapse of an O-Ne-Mg core, rather than by collapse of an Fe core due to photodissociation.

Fesen & Becker (1990), Leibundgut et al (1991b), and Fesen & Matonick (1993, 1994; see also Fesen et al 1995) illustrated very late-time spectra of SNe II-L 1980K and 1979C. Additional objects having similar characteristics include SN 1970G (Fesen 1993) and SN 1986E (Cappellaro et al 1995b). The spectra consist of a few strong, broad emission lines such as Hα, [O I] $\lambda\lambda$6300, 6364, and [O III] $\lambda\lambda$4959, 5007. Their relative intensities and temporal changes are generally consistent with the circumstellar interaction models of Chevalier & Fransson (1994), and they can be used to further constrain the nature of the progenitor star.

5.4 *Type IIn Supernovae*

During the past decade, there has been the gradual emergence of a new, distinct subclass of SNe II (Filippenko 1991a,b, Schlegel 1990, Leibundgut 1994) whose ejecta are believed to be strongly interacting with dense circumstellar gas (see Chevalier 1990 for an overview of this process). The derived mass-loss rates for the progenitors can exceed $10^{-4} M_\odot$ year^{-1} (Chugai 1994b). In these objects, the broad absorption components of all lines are weak or absent throughout their evolution. Instead, their spectra are dominated by strong emission lines, most notably Hα, that have a complex but relatively narrow profile. Although the details differ among objects, Hα typically exhibits a very narrow component (FWHM $\lesssim 200$ km s^{-1}) superposed on a base of intermediate width

(FWHM $\approx$ 1000–2000 km s^{-1}; sometimes a very broad component (FWHM $\approx$ 5000–10,000 km s^{-1}) is also present. Schlegel (1990) christened this subclass "Type IIn," the "n" denoting "narrow" to emphasize the presence of the intermediate-width or very narrow emission components. Representative spectra of five SNe IIn are shown in Figure 14, with two epochs for SN 1994Y.

The early-time continua of SNe IIn tend to be bluer than normal. Occasionally He I emission lines are present in the first few spectra [e.g. SN 1994Y in Figure 14 and SN 1987B (see Figure 1.22 of Harkness & Wheeler 1990)]. Very narrow Balmer absorption lines are visible in the early-time spectra of some of these objects, often with corresponding Fe II, Ca II, O I, or Na I absorption as well (e.g. SNe 1994W and 1994ak in Figure 14). Some of them are unusually luminous at maximum brightness, and they generally fade quite slowly, at least at early times. The equivalent width of the intermediate Hα component can grow to astoundingly high values at late times.

One of the first extensively observed SNe IIn was SN 1987F (Filippenko 1989a, Wegner & Swanson 1996). Initially, broad Hα emission was superposed on a luminous ($M_V \approx -19.3$ mag), nearly featureless continuum, but its profile did not have the characteristic P Cygni shape, and its centroid was blueshifted by $\gtrsim$1500 km s^{-1} with respect to the systemic velocity of the parent galaxy. Many months later, the broad Hα in SN 1987F was more luminous and had much larger equivalent width; Fe II, Ca II, and O I emission were detected as well (see also SN 1994Y in Figure 14). Forbidden lines, normally prominent at this phase, were very weak; Filippenko (1989a, 1991a) concluded that the ejecta had high electron density ($n_e \gtrsim 10^9$ cm^{-3}). The narrow component of Hα, initially quite luminous, was now much weaker. At early times it may have been produced by material previously lost from the progenitor, but this gas was eventually engulfed by the expanding SN ejecta. At 10 months after maximum, SN 1987F was $\sim$2-mag more luminous than typical SNe II-P (Cappellaro et al 1990). Chugai (1991) modeled the data according to an interaction of the SN ejecta with dense circumstellar matter.

Another example is SN 1988Z (Filippenko 1991a,b, Stathakis & Sadler 1991, Turatto et al 1993b, Chugai & Danziger 1994). At early times, SN 1988Z showed very narrow (FWHM $\lesssim$ 100 km s^{-1}) [O III] λ4363 and [O III] $\lambda\lambda$4959, 5007 emission lines whose relative intensities indicated $n_e \gtrsim 10^7$ cm^{-3}. They were almost certainly produced by circumstellar gas released by the progenitor prior to exploding and then photoionized by the intense flash of UV radiation emitted at the time of shock breakout. A resolved, intermediate-width (FWHM $\approx$ 2000 km s^{-1}) component of Hβ appeared less than two months after discovery and steadily grew stronger. At Hα, this component was superposed on a much broader emission line (FWHM $\approx$ 15,000 km s^{-1}; see Figure 14). Nearly a year later, the intermediate-width component completely dominated the optical

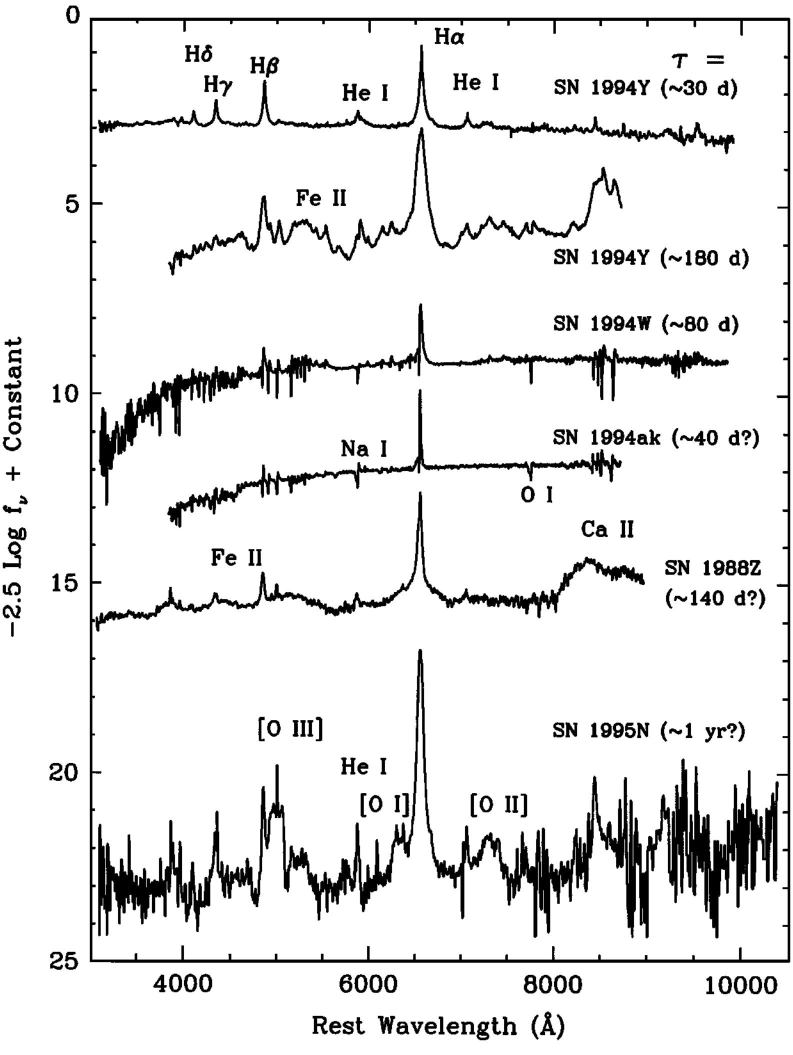

Figure 14 Montage of spectra of SNe IIn. The objects, UT dates of observation, parent galaxies, and adopted redshifts (kilometers per second) are as follows: SN 1994Y (September 1, 1994 and January 26, 1995; NGC 5371; 2553), SN 1994W (October 1, 1994; NGC 4041; 1234), SN 1994ak (January 26, 1995; NGC 2782; 2562), SN 1988Z (April 27, 1989; MCG+03-28-022; 6595), and SN 1995N (May 24, 1995; MCG +02-38-017; 1534). Epochs are given relative to the estimated dates of explosion rather than maximum brightness; the rise times to maximum can differ substantially among SNe IIn.

spectrum (Filippenko 1991a,b, Turatto et al 1993b). Its Balmer decrement was very steep, possibly indicating "Case C" recombination conditions (e.g. Xu et al 1992) in which the gas is optically thick to the Lyman and Balmer series, although collisional excitation may have also contributed to the peculiar line intensity ratios. We were probably seeing shock-induced emission from dense clumps in a wind emitted by the progenitor star (Chugai & Danziger 1994). As in SN 1987F, forbidden lines were weak or absent, and very strong lines of Fe II, Ca II, and O I emerged (Figure 14). The blend of O I λ8446 and the Ca II near-IR triplet, in particular, became stronger than the very broad component of Hα, yet little or no [Ca II] $\lambda\lambda$7291, 7324 was present, indicating high density. However, Chugai & Danziger (1994) argued that the envelope was not massive, and hence the progenitor itself may have had a relatively low mass, in contrast with the conclusion of Stathakis & Sadler (1991).

The late-time optical spectra of SN 1988Z closely resembled those of SN 1986J, an object that was discovered at radio wavelengths long after its optical outburst (Rupen et al 1987, Leibundgut et al 1991b). Accordingly, Filippenko (1991a) predicted that SN 1988Z should eventually become very luminous at radio wavelengths, as did SN 1986J. SN 1988Z was indeed subsequently detected at radio wavelengths with a luminosity comparable to that of SN 1986J, and analysis of the radio light curves suggested a high mass-loss rate (Van Dyk et al 1993). SN 1988Z was also detected as an X-ray source (Fabian & Terlevich 1996). Another similar object is SN 1978K (Ryder et al 1993, Chugai et al 1995), which was luminous at radio and X-ray energies, although its Balmer decrement was not unusually steep and suggests Case B recombination.

Type IIn supernovae exhibit considerable heterogeneity. For example, objects like SNe 1986J, 1988Z, 1993N (Filippenko & Matheson 1993, 1994), and 1995N (Pollas et al 1995, Garnavich et al 1995a, Van Dyk et al 1996b), whose spectra were for many years completely dominated by Hα emission of FWHM $\approx$ 1000 km s^{-1}, became strong radio and X-ray sources. They seem to have the densest circumstellar material. Of these objects, the ones observed at early times (SNe 1988Z and 1993N) had relatively featureless blue continua with almost no Hα emission. Other SNe IIn, however, are distinct from the SN 1988Z flavor; they exhibit strong Hα emission right from the start (e.g. SN 1994Y in Figure 14), and they don't become luminous radio sources (Van Dyk et al 1996c). Even among these latter objects there is considerable heterogeneity: Witness the presence of narrow absorption lines in SN 1994W (and also SN 1994ak) but not in SN 1994Y (Figure 14). Moreover, as illustrated by Cumming & Lundqvist (1997), the brightness of SN 1994W dropped precipitously after an age of four months, while SN 1994Y remained quite bright for several years after outburst (AV Filippenko, unpublished data). As another example, the early-time spectrum of SN 1987B (Harkness & Wheeler 1990, Filippenko 1991b, Schlegel et al 1996) closely resembled that of SN 1994Y

(Figure 14), with Balmer emission lines and He I that had broad bases; on the other hand, a few months later, the spectrum of SN 1987B exhibited only a hint of broad emission and was instead dominated by relatively narrow absorption lines (Filippenko 1991b), while that of SN 1994Y showed broad Balmer and Fe II emission lines (Figure 14).

SN 1983K (Niemela et al 1985), despite its classification as a SN II-P by Phillips et al (1990), might also be a variant of SNe IIn and further illustrates the diversity of this subclass: Emission lines of N III λ4651 and He II λ4686, as well as hydrogen Balmer emission lines, were superposed on a very blue continuum in spectra obtained about 10 days prior to maximum brightness, but by maximum brightness the spectrum showed only a few weak and narrow absorption lines. In the case of SN 1984E (Henry & Branch 1987), there was evidence that circumstellar material had been ejected from the progenitor in a relatively discrete event less than 30 years before the explosion (Gaskell & Keel 1988, but see Dopita et al 1984). Recently there have been a substantial number of other SNe IIn discovered (as documented in *IAU Circulars*), and they seem to exhibit a great variety of properties that should provide clues to the nature of mass loss in evolved massive stars.

5.5 *Links Between SNe II and SNe Ib/Ic*

5.5.1 SN 1987K SN 1987K (Figure 15) appears to be a link between SNe II and SNe Ib (Filippenko 1988). Near maximum brightness, it was undoubtedly a SN II but with rather weak photospheric Balmer and Ca II lines. Many months after maximum, the broad Hα emission that dominates the late-time spectra of other SNe II was weak or absent. Instead, broad emission lines of [O I] $\lambda\lambda$6300, 6364, [Ca II] $\lambda\lambda$7291, 7324, and the Ca II near-IR triplet were the most prominent features, just as in SNe Ib. Such a metamorphosis was, at that time, unprecedented in the study of SNe.

SN 1987K provides very strong evidence for a physical continuity between the progenitors and explosion mechanisms of SNe II and at least some SNe Ib/Ic. The simplest interpretation is that SN 1987K had a meager hydrogen atmosphere at the time it exploded (but see Harkness & Wheeler 1990); it would naturally masquerade as a SN II for a while, and as the expanding ejecta thinned out the spectrum would become dominated by emission from deeper and denser layers. It is noteworthy that, aside from the Hα line, the early-time spectrum of SN 1987K was actually quite similar to those of SNe Ic 1983I and 1983V (Wheeler et al 1987). The progenitor was probably a star that, prior to exploding via iron core collapse, lost almost all of its hydrogen envelope either through mass transfer onto a companion or as a result of stellar winds.

5.5.2 SN 1993J The data for SN 1987K (especially its light curve) were rather sparse, making it difficult to model in detail; moreover, it was an apparently

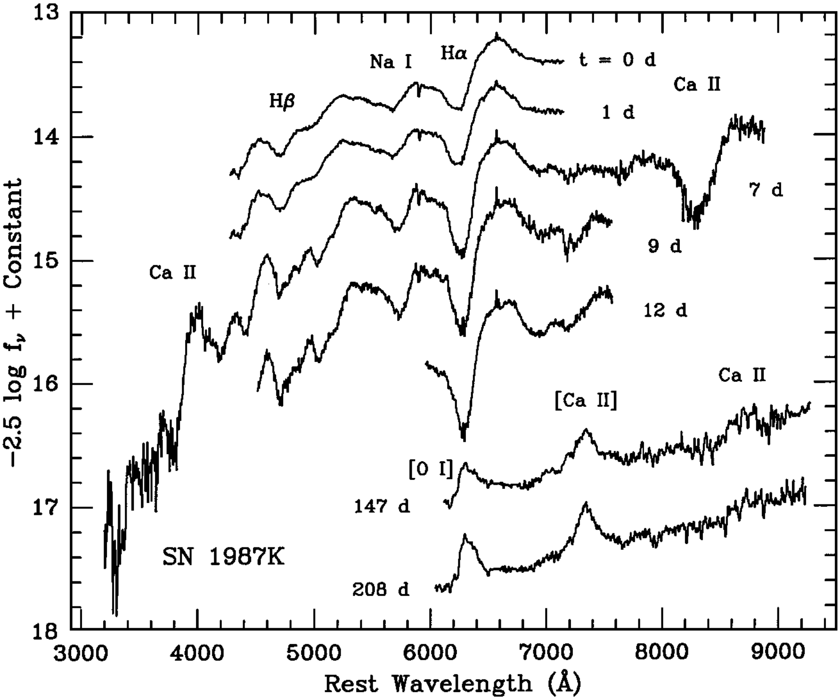

Figure 15 Montage of spectra of SN 1987K in NGC 4651 ($cz = 817$ km s^{-1}), showing the dramatic transformation from a SN II to a SN Ib. Narrow emission lines, produced by superposed H II regions, have been excised in the late-time spectra. Adapted from Filippenko (1988). Epochs are given relative to the date of maximum brightness, July 31, 1987.

unique object and hence perhaps somewhat of a fluke. Consequently, there may have been some room for skepticism regarding the connection between SNe II and SNe Ib (dubbed "SNe IIb" by Woosley et al 1987, who had proposed a similar preliminary model for SN 1987A before it was known to have a massive hydrogen envelope; see Arnett et al 1989). Fortunately, the Type II SN 1993J in NGC 3031 (M81) came to the rescue. Bright ($V \gtrsim 10.7$ mag), nearby ($d =$ 3.6 Mpc; Freedman et al 1994), and well placed in the night sky (circumpolar for many northern observatories), it was studied in greater detail than any SN since SN 1987A. Its early history of observations and modeling is documented by Wheeler & Filippenko (1996).

The unusual nature of SN 1993J first became apparent through its light curves (Benson et al 1994, Lewis et al 1994, Richmond et al 1994, 1996a, Barbon et al 1995, Prabhu et al 1995). At visual wavelengths, it rose to maximum brightness in just a few days, then plummeted by ~1.3 mag over the next week, and subsequently climbed for two weeks to a second peak of brightness comparable to the first. Thereafter it declined, initially about as rapidly as the second rise. By ∼40 days after the explosion, it had settled onto an exponential tail of ∼0.02 mag day^{-1}. This behavior differed substantially from that of either the "plateau" or "linear" SNe II (Barbon et al 1979, Doggett & Branch 1985). The rapid initial rise and the twin peaks were reminiscent of SN 1987A, but the time scale of SN 1993J's second peak was much shorter.

A number of independent groups quickly concluded that the progenitor of SN 1993J probably had a relatively low-mass hydrogen envelope (Nomoto et al 1993, Podsiadlowski et al 1993, Ray et al 1993, Bartunov et al 1994a, Utrobin 1994, Woosley et al 1994); otherwise, the second peak would have resembled the more typical plateau of SNe II, since stored energy slowly diffuses out of a massive envelope. Indeed, Nomoto et al (1993) pointed out that the second rise and decline closely resembled the light curve of SN 1983N (Clocchiatti et al 1996b), a prototypical SN Ib. Most groups found that the light curve could be modeled well by assuming that the progenitor was a ∼4 $M_{\odot}$ He core having a low-mass (0.1–0.6 $M_{\odot}$) "skin" of hydrogen; the explosion mechanism was the standard iron core collapse of SNe II.

The likely progenitor of SN 1993J was identified as a G8I-K5I star with a bolometric magnitude of about −7.8 (Aldering et al 1994, Garnavich et al 1997). The general consensus (for a dissenting view, see Höflich et al 1993) is that its initial mass was ∼15 $M_{\odot}$. A star of such low mass cannot shed nearly its entire hydrogen envelope without the assistance of a companion star. Thus, the progenitor of SN 1993J probably lost most of its hydrogen through "Case C" mass transfer (in the asymptotic giant phase, after core He burning) to a bound companion 3- to 20-AU away. In addition, part of the gas may have been lost from the system.

A specific prediction made by Nomoto et al (1993) and Podsiadlowski et al (1993) was that the spectrum of SN 1993J should evolve to resemble those of SNe Ib/Ic, as in the case of SN 1987K described in Section 5.5.1. Nearly simultaneously with the submission of these papers, Filippenko et al (1993) identified prominent absorption lines of He I in SN 1993J, confirming the prediction. Instead of growing progressively more prominent with time (relative to other features), the emission component of Hα developed a distinct notch identified as blueshifted He I λ6678 (see Figure 16). Swartz et al (1993a) came to essentially the same conclusion: The spectrum of SN 1993J was transforming itself into that of a SN Ib together with a bit of hydrogen.

Filippenko et al (1993) suggested that many months after the explosion, the spectrum of SN 1993J would closely resemble the late-time spectra of SNe Ib—dominated by strong emission lines of [O I], [Ca II], and Ca II, with Hα weak or absent (cf SN 1987K). This was confirmed by Filippenko et al (1994; see

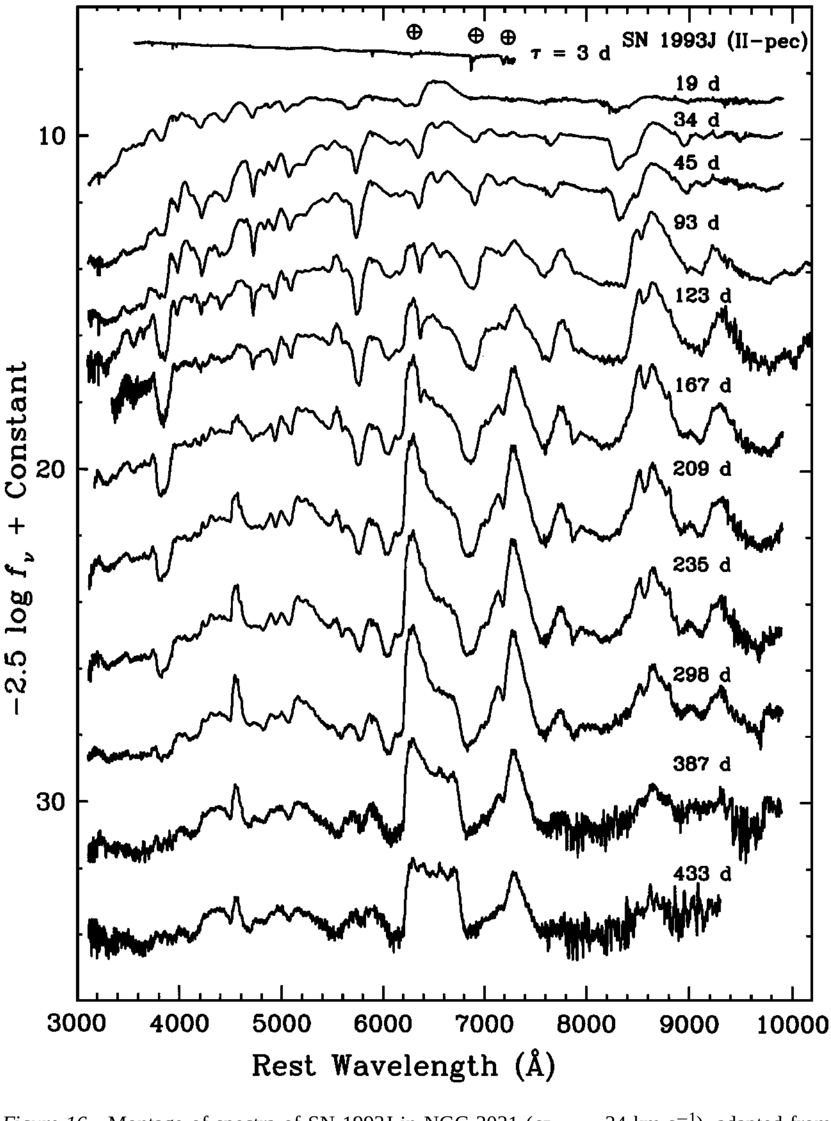

Figure 16 Montage of spectra of SN 1993J in NGC 3031 ($cz = -34$ km s^{-1}), adapted from Filippenko et al (1994). Epochs (days) are given relative to the estimated date of explosion, March 27.5, 1993. There are a few telluric features in the first spectrum.

also Finn et al 1995), as illustrated in Figure 16. Although Hα remained visible throughout the evolution of SN 1993J, it was weak relative to the neighboring [O I] line at $\tau = 6$–10 months, whereas in normal SNe II it dominates the optical spectrum at these epochs (e.g. Figure 12). The emission lines were considerably broader than those of normal SNe II at comparable phases, which is consistent with the progenitor having lost a majority of its hydrogen envelope prior to exploding.

The photometric behavior during the first four months (twin peaks; 0.02-mag day^{-1} exponential decline), together with the spectral evolution, strongly suggests that the progenitor of SN 1993J had only a low-mass skin of hydrogen. Moreover, the V-band decline rate at very late times ($\sim$0.014 mag day^{-1} at $\tau \approx 300$ days; Richmond et al 1996a) was substantially steeper than that of normal SNe II (0.009 mag day^{-1}) and comparable to that of SNe I (Turatto et al 1990), again indicating a low mass for the ejecta. Had the progenitor lost essentially all of its hydrogen prior to exploding, it would have had the optical characteristics of SNe Ib. Consequently, there is now little doubt that most SNe Ib, and probably SNe Ic as well, result from core collapse in stripped massive stars rather than from the thermonuclear runaway of white dwarfs. In addition, it seems likely that a good fraction of the progenitors lost their mass largely via transfer to a bound companion rather than with winds. These conclusions have broad implications for the chemical evolution of galaxies, the expected number density of compact remnants, the potential detectability of neutrino bursts, and the origin of X-ray binary stars.

SN 1993J held several more surprises, however. Observations at radio (Van Dyk et al 1994) and X-ray (Suzuki & Nomoto 1995) wavelengths revealed that the ejecta were interacting with relatively dense circumstellar material (Fransson et al 1996), probably ejected from the system during the course of its pre-SN evolution. Optical evidence for this interaction also began emerging at $\tau \gtrsim 10$ months: The Hα emission line grew in relative prominence, and by $\tau \approx$ 14 months it had become the dominant line in the spectrum (Filippenko et al 1994, Finn et al 1995, Patat et al 1995), consistent with the model of Chevalier & Fransson (1994). Its profile was very broad (FWHM $\approx$ 17,000 km s^{-1}; Figure 16) and had a flat top, but with prominent peaks and valleys whose likely origin is Rayleigh-Taylor instabilities in the cool, dense shell of gas behind the reverse shock (Chevalier et al 1992). (The late-time emergence of Hα is the main reason SN 1993J is listed as a "SN II-pec" in Figure 16; otherwise, it is a prime example of SNe IIb.) Radio VLBI measurements showed that the ejecta are circularly symmetric but with significant emission asymmetries (Marcaide et al 1995), which are possibly consistent with the asymmetric Hα profile.

5.5.3 IS THERE HYDROGEN IN OTHER SNe Ib/Ic? In view of the prominence of Hα in the first few spectra of SNe 1987K and 1993J, and the resemblance between the late-time spectra of these two SNe II and SNe Ib/Ic, the search for hydrogen in the spectra of SNe Ib/Ic is of interest. Perhaps it is present in some cases but at a lower level than in the "SN IIb" prototypes; this would set more constraints on the nature of the progenitors.

Wheeler et al (1994) pointed out a possible Hα absorption line in spectra of the prototypical SNe Ib 1983N and 1984L. Similarly, Branch (1972) noted that SN Ib 1954A may have exhibited Hα. The presence of weak Hα in SNe Ib is not unexpected, given the examples of SNe 1987K and 1993J; the entire hydrogen envelope need not be expelled prior to core collapse, regardless of whether the progenitor loses gas primarily through winds (very massive star, either isolated or in a wide binary) or via transfer to a companion.

Filippenko (1988, 1992) suggested that SNe Ic 1987M, 1988L, and 1991A had weak Hα emission; SN 1987M may also have exhibited Hα absorption (Filippenko et al 1990, Jeffery et al 1991). If hydrogen is indeed present in some SNe Ic, then SNe Ic cannot be the explosions of isolated type-WC Wolf-Rayet stars—i.e. those that have lost their entire H envelope and much of their He layer as well. [Note that Van Dyk et al (1996a) also argued against the WR progenitor model, based on a study of the association of SNe Ib/Ic with H II regions.] The binary scenario of Shigeyama et al (1990), on the other hand, may be consistent with a weak Hα line, since a helium layer (perhaps with some remaining hydrogen on it, or mixed with it) is present. However, there are other problems with this model—especially the absence of prominent He I lines (Baron 1992). Indeed, the spectral synthesis of Swartz et al (1993b) demonstrated that the progenitors of SNe Ic cannot even have much helium, let alone hydrogen, in their outer layers—if they did, then the signature of these elements would easily be visible at early times.

6. FINAL REMARKS

This review has emphasized the optical spectral classification of SNe. The approach is largely taxonomical—or, in the style of Zwicky (1965), "morphological." Like botanists and zoologists, we wish to find observable characteristics that eventually provide a deeper physical understanding of the objects under consideration. Naturally, certain properties may turn out to be more useful than others, and it is our goal to identify these.

For example, a clue to whether SNe Ib and SNe Ic are physically different might be provided by the degree to which the He I line strengths form a continuous sequence among the two subclasses; a roughly bimodal distribution could indicate distinct progenitors or evolutionary paths. Similarly, if the observed properties of SNe IIn really do result from unusually dense circumstellar media, they will provide information on stellar mass loss under different circumstances.

The apparent similarity of the early-time spectra of SNe Ic and subluminous SNe Ia (Filippenko et al 1992a), on the other hand, may end up being nothing more than an indication of comparable primordial iron abundances in the atmospheres of the progenitors, as suggested by Clocchiatti & Wheeler (1997).

There is a tendency to assign each object to a new pigeonhole, based on small variations in the spectra or light curves. This should generally be resisted, unless there are clear physical grounds for doing so (as in the case of SNe IIb), because the proliferation of subtypes having few known members generally does not enhance our understanding of the nature of the phenomenon. For instance, the unusual strength of Ba II lines in early-time spectra of SN 1987A (Williams 1987), though interesting and important to understand, does not justify the creation of a new subclass. Of course, deviants often give valuable clues that are otherwise difficult to notice or entirely unavailable, and considerable attention should be paid to them. Good examples are provided by the peculiar SNe Ia 1991T and 1991bg, which dramatically illustrate the heterogeneity of SNe Ia and considerably strengthen the apparent correlation between luminosity and decline rate.

The greatest benefits, of course, are often achieved when many different types of observations are combined. For example, optical polarimetry and spectropolarimetry, though not discussed here owing to space limitations, can give information on asymmetries in the ejecta of SNe (e.g. Jeffery 1991, Höflich et al 1996b). Similarly, the recent work of Clocchiatti & Wheeler (1997) showed that SNe Ic with essentially identical spectra can be distinguished by their optical light curves, perhaps indicating rather important differences in the internal structure of the ejecta. IR emission is prominent throughout the evolution of SNe and thoroughly dominates at late times. Conditions at the time of shock breakout are best studied at UV wavelengths, X-ray and radio observations provide clues to the circumstellar environment of SNe, gamma-ray data are used to study the products of explosive nucleosynthesis, and neutrinos can indicate whether a neutron star was formed. The observational study of SNe is a rich and active field; this review was necessarily restricted to only a small subset of the relevant data.

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