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超新星光谱研究的进展：观测

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摘　　要

介绍了超新星完整样品的分类概况，依次转述了各类超新星光谱观测的新进展。两颗特殊 Ia 型超新星 —SN1991T 和 SN1991bg— 的发现对原先认为 Ia 型超新星是均质的观点提出了挑战；对 Ib/Ic 型超新星应加以特别关注。II 型超新星 SN1993J 和 SN1987K 由光极大时的 II 型演化到星云相类似于 Ib/Ic 的光谱，对传统的超新星 I 型和 II 型的区分提出了质疑。对某些特殊 II 型超新星也许列为 “ II n ” 型，其 Hα 谱线轮廓呈现为宽发射线上部叠加上一条窄的尖锋。由距离远的 II 型超新星 1992am 推算出的哈勃常数 $H_0 = 80^{+17}_{-15}\mathrm{km\cdot s^{-1}\cdot Mpc^{-1}}$ 。

关 键 词　超新星：一般 — 谱线：证认

Progress in the Spectral Studies of Supernovae: Observation

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Abstract

A classification scheme is described for the whole sample of supernovae (SNe). Progress in the spectral observations of various types of SNe is reported. The discoveries of two peculiar SN Ia - SN 1991T and SN 1991bg challenged the reliability of the homogenity of the Type Ia class. Particular attention should be paid to the sample of Type Ib/Ic SNe. The evolution from Type II SNe at maximum light to Type Ib/Ic SNe at later times for SN 1993J and SN 1987K raised questions on the traditional Type I–Type II differentiation. A new subclass of "Type II n" may be needed for the Type II SNe showing peculiar Hα profiles, with narrow peaks sitting on broad emission bases. A Hubble constant of $H_0 = 80^{+17}_{-15}\mathrm{km\cdot s^{-1}\cdot Mpc^{-1}}$ is obtained from

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observations of a distant Type II SN 1992am.

Key words Supernovae: general—line: identification

1 Introduction

Ever since the spectrum of a supernova was first observed in 1885, astronomers have known that a correct reading of the spectrum would reveal otherwise unattainnable information about the physical conditions and composition of the radiation source. As emphasized by Filippenko (1988)[1] and others, optical spectra should be used as the primary discriminants for the classification of SNe, so it is very desirable that at least one spectrum should be obtained for every SN discovered. Moreover, as the envelope of a SN evolves from optical–thick at maximum light to optical–thin at later times, its spectra will evolve from photospheric phase to nebular phase, revealing each layers of the "onion–like" structure of its progenitor (SN II, SN Ib), so by studying them we can gain new sights into the whole course of stellar evolution.

The observations and theories of the spectra of SNe have increased dramatically during the last decade, so we present a review here, giving more emphasis on the observations. Section 2 describes a classification scheme for the SNe, and from section 3 through section 5 new results of the observation of each type of SNe are described.

2 The Basic Spectral Types of SNe

SNe are primarily classified by their spectral evolution with some consideration of their light curve morphology. Figure 1 shows the basic classification scheme. The classification traditionally depends on the spectrum near maximum light. The basic differentiating property was Whether or not the showed evidence of hydrogen. If so, the event was classified as Type II, if not, Type I[2].

Among the SN II events a further differentiation was proposed based on the shape of the light curve. Those with a pronounced plateau are termed type II plateau (SN II-P) and those with a nearly linear decline in magnitude with time from peak are termed type II linear (SN II-L)[3]. A third subclass is added with the advent of SN 1987A. The light curve of SN 1987A was very different from other Type II SNe due to the blue compact nature of its progenitor, although it showed some similarity to SN II-P on the exponential tail[4].

Type I SNe can be sub-classified according to the features of the spectra at maximum light[5,6]. The key for sub-classification is the presence or absence of the strong Si II absorption feature at 6150Å. Classical type Ia events show this strong Si P-Cygni feature. Others do not, and they have come to be known as a separate subclass. The events that fail to show the strong Si feature near maximum light can be further differentiated by the presence or absence of strong lines of helium[7]. The event that shows no Si near maximum light, while does show He I, especially

He Iλ 5876 is identified as Type Ib. There are other events that fail to show either H or Si near maximum light, while show only weak evidence for He. Wheeler *et al* (1986)[7] proposed the category SN Ic for these events.

However, more and more observations have challenged this classification scheme, as discussed in detail in the following sections.

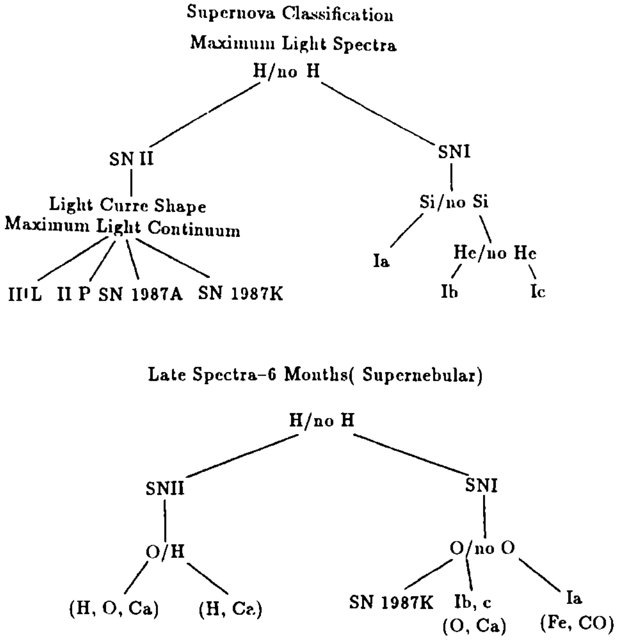

Fig.1 The basic classification scheme of SNe

3 Type Ia SNe

Type Ia SNe are well-known as a nearly homogeneous class of SNe. However, observations of the peculiar Type Ia SN 1991T and SN 1991bg, together with a recent paper by Phillips (1993)[8], have drawn attention to the diversity among Type Ia class. With a sample of 9 SNe Ia, Phillips (1993)[8] found that the peak absolute magnitudes in the B, V, and I bands correlate with the decline rate of the immediate postpeak light curve. Different slopes of the magnitude–decline relations in the three bands imply that the colors at maximum light also correlate with decline rate. Thus SNe Ia can be arranged in a photometric sequence, from luminous blue events with relatively slowly declining light curves, like SN 1991T, to subluminous red ones with rapidly declining light curves like SN 1991bg. As discussed further below , it seems that when arranged in the photometric sequence, SNe Ia also form a spectroscopic sequence. This aspect of Type Ia SNe has interesting implications for physical models of SNe Ia, and for the use of SNe Ia as distance indicators.

The appearance of two quite peculiar SNe Ia in the same year , 1991, seems to have caused many astronomers to wonder whether the term "normal Type Ia supernova" has lost its meaning. How rare or common are the most extreme events such as SNe 1991T and 1991bg? Branch *et al* (1993)[9] addressed this question in terms of optical spectra. They defined a normal SN Ia as one whose optical spectra resembled those of SNe 1981B[10], 1989B[11,12], 1992A[13], and 1972E[14] rather than those of the peculiar SNe 1991T, 1991bg, or 1986G. Figure 2 shows the spectral evolution of SN 1989B. Normal SNe Ia near maximum light show conspicuous absorption features near 6150Å due to Si II and near 3750 Å due to Ca II. Other absorptions appear near 4000 Å(Si II, Co II), 4300 Å(Mg II, Fe II), 4900 Å(Si II, S II), 5300 and 5500 Å(S II), 5700 Å(Si II), 7500 Å(O I, Mg II), and 8200 Å(Ca II). The physical picture is that the maximum light spectrum forms in outer, high-velocity layers of the explosion which have been burned mainly to intermediate-mass elements from oxygen to calcium, while the postmaximum spectra form in deeper, slower layers which consist mainly of iron-peak elements.

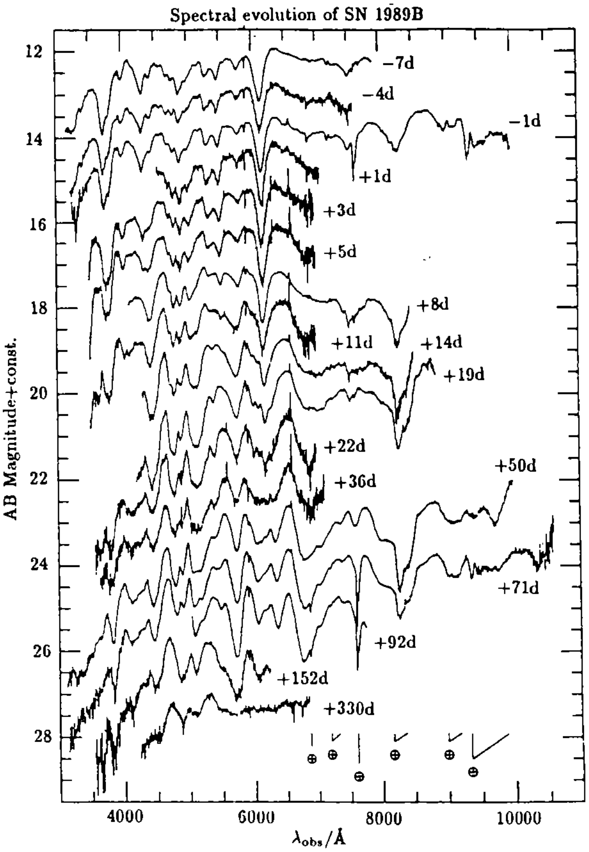

Fig.2 A sampling of optical spectra obtained of SN 1989B illustrating the evolution from six days before B maximum to a year later

The spectroscopically peculiar SN Ia is defined as one that has feature strengths (not just expansion velocity) that differ from the norm at a given phase. So far we have three well observed examples, SNe 1991T, 1991bg, and 1986G. Fig.3 shows the comparison of their spectra with two normal Type Ia SNe. SN 1991T[15,16,17] near maximum light shows unusually weak lines of Si II, S II, and Ca II, and prominent features of Fe III. The spectroscopic peculiarities of SN 1991T appear to be due to an enhanced production of iron-peak elements at the expense of intermediate-mass elements such as Si, S, and Ca in the outer layers of the supernova[18] SN 1991bg[19,17] shows the presence of a broad absorption trough extending from about 4150 to 4400 Åwhich were probably produced by a blend of Ti II lines, accompanied by a fairly deep absorption near 5000 Å also due to Ti II. The spectroscopic indications are that SN 1991bg underproduced iron–peak elements, consistent with the photometric indications that it was subluminous and cool. SN 1986G[20,21] is similar to SN 1991bg but it is a less extreme event.

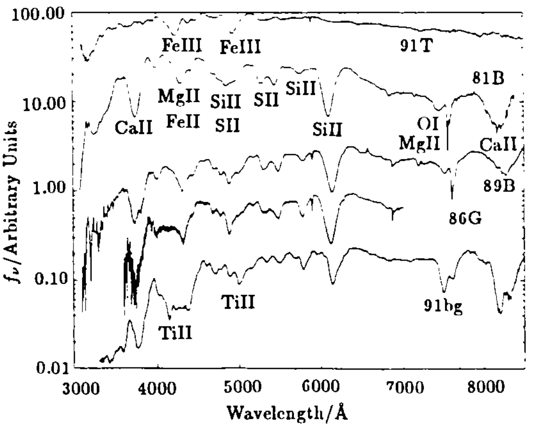

Fig.3 Comparison of near-maximum light spectra of two normal SN Ia and three peculiar SN Ia (SN 1991T, SN 1986G, SN 1991bg).

4 Type Ib/Ic SNe

SNe without spectral evidence of hydrogen and with evidence for He are classified as Type Ib. SNe that show neither strong evidence for H and He nor the strong blend of Si II λ 6355 and show strong absorption of O I λ7774, are termed Type Ic. Wheeler et *al* (1987)[22] originally proposed categories of "helium-rich" and "helium-poor". Subsequently Harkness & Wheeler (1990)[23] and Wheeler & Harkness (1990)[24] advocated the specific terminology of Type Ib and Type Ic in order to focus on the differences in the spectra that signify some significant difference in the progenitor evolution.

Type Ib SNe are characterized by the absence of conspicuous Balmer lines near maximum, and the presence of strong absorption lines of He I in the month or so after maximum. The late emission line phase is reminiscent of canonical Type II but with no detectable optical evidence for either H or He. The nebular spectrum shows strong lines of Mg] λ4571, Na D, [O I] $\lambda\lambda$6300,6364, [Ca II] $\lambda\lambda$7291: 7323,and the CaII IR triplet. Radio emmission was detected from some Type Ib SNe, suggesting the presence of a rather substantial circumstellar medium.

Type Ic SNe are characterized by the absence of evidence for both H and He in optical spectra both near maximum, and in the month or two after maximum. Near maximum the spectrum is characterized by a strong absorption of O I λ7774 and an absorption of Si II λ6355 that is considerably weaker than for Type Ia and otherwise by features that are mostly blends of Fe II. In the nebular emission line phase the spectra resemble those of Type Ib SNe.

A significant component of the discussion of the nature of the Type Ic category has been a controversy over whether there is evidence for H in the spectra. Filippenko *et al* (1990)[25] say that the local maximum near 6500 Å in SN Ic 1987M might be Hα. Jeffery *et al* (1991)[26] argued that the minimum at 6370 Å was , indeed, Hα and that the minimum at 6170 Å was Si. To achieve this agreement, the abundances of O and Si had to be altered from solar ratios and the H was assigned a rather low velocity of 8900 km $\cdot$ s^{-1} compared to O I λ7773 at 10300 km$\cdot$s^{-1} and especially compared to the Ca II lines at about 14000 km$\cdot$s^{-1}. The velocity inconsistency, in particular, is a major problem with this interpretation.

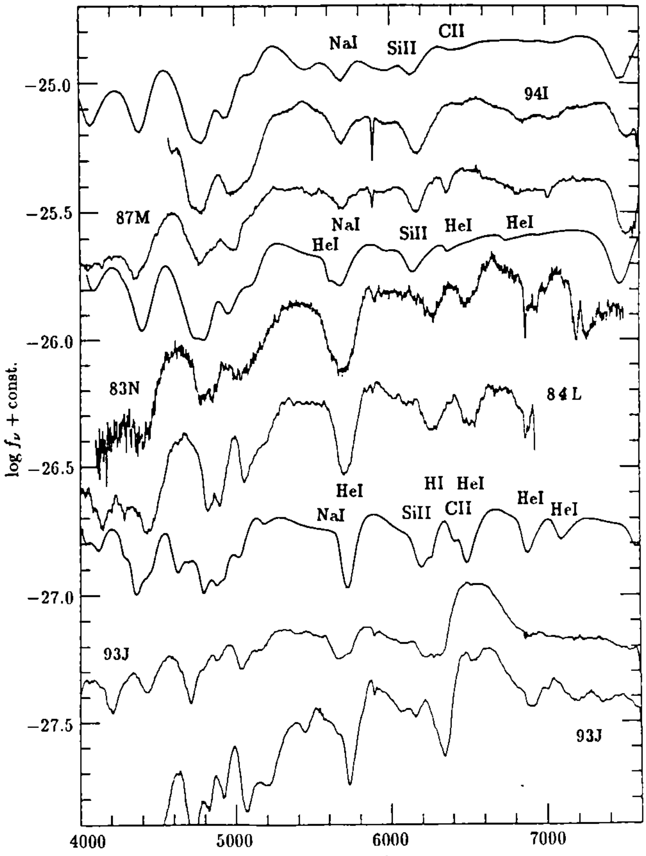

Fig.4 Spectra are given for SN 1994I, SN 1987M, SN 1983N, SN 1984L and SN 1993J

The most recently observed Type Ic supernova was SN 1994I in M51. A spectrum of SN 1994I is shown in figure 4 , together with the spectra of two SNe Ib 1983N and SN 1984L and another SN Ic 1987M and SN 1993J[27]. The spectrum of SN 1994I was obtained from McDonald Observatory on UT April 10.17, in coincidence with maximum in B. The spectrum is very similar to that of SN 1987M on Sep 28 1987 with the exception of the feature at 6370 Å which is much weaker, or absent. The lines of He are extremely weak, if present at all. Subsequent optical spectra did not show an increased strength of the He I line series. SN 1994I belongs to the "helium-poor" category, i.e., it is a Type Ic event.

5 Type II SNe

A major challenge to the above mentioned classification scheme emerges in the category of Type II SNe. In the last decade many peculiar Type II SNe were observed and they deserve detailed study to investigate their implication to the spectral classification scheme of SNe. SN 1987A is an extreme events that has been intensively studied, but we exclude it in this paper as it was reviewed in the present journal before. The following paragraghs discussed some of other peculiar Type II SNe in more detail.

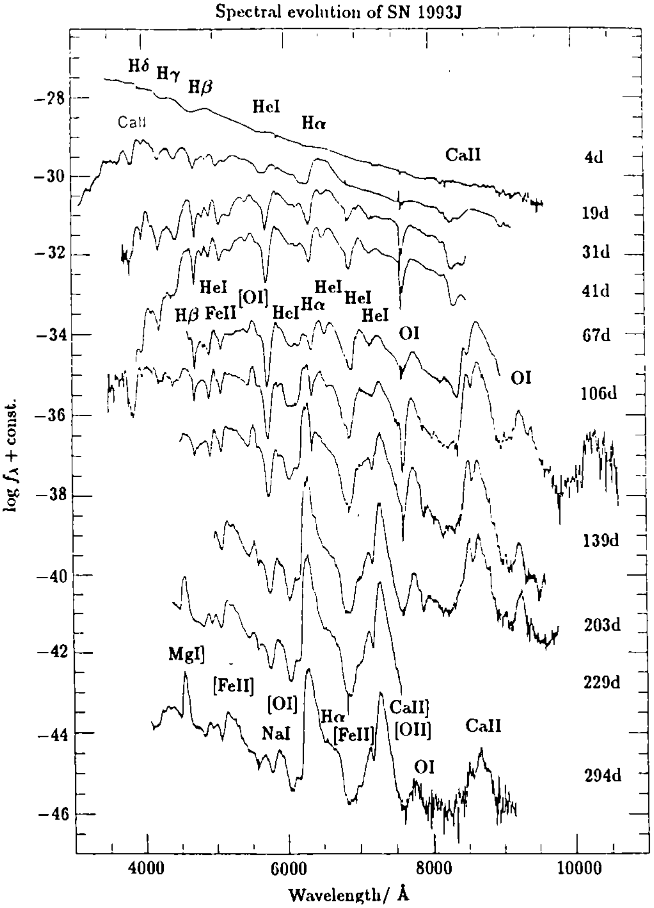

Fig.5 The spectral evolution of SN 1993J.

5.1 SN 1993J and SN 1987K

SN 1993J was classified as a Type II SN because it showed strong Balmer lines in its maximum–light spectra. However, about 26 days after explosion, the spectra of SN 1993J began to deviate significantly from those of typical Type II SNe, in that the Hα emission profile shows a "double–peaked" structure due to the effects of the He I λ6678 line[28]. Several months later the Hα feature was almost entirely eaten by the He I line and the spectrum resembled a Type Ib/Ic SN (see Fig. 5). The spectrum of SN 1993J obtained almost nightly by 2.16-m telescope at Beijing Astronomical Observatory has greatly increased the understanding of this peculiar supernova in the world.

SN 1987K was studied in detail by Filippenko (1988). At maximum light it showed a strong P–Cygni feature at around 6300 Åwhich might be Hα so the event was identified also as an SN II. Two weeks past maximum, the strengths of the Hα emission–line and absorption–line were much smaller than those in SN 1987A. Several months later, no trace of the broad Hα can be found; instead, very broad emission lines of [O I] and [Ca II] dominate the spectrum. These last characteristics are typical of Type Ib/Ic SNe long past maximum.

So it is a perplexed problem to put SN 1987K and SN 1993J in the classification scheme. Their evolution from Type II SNe at maximum light to Type Ib/Ic at later times has impelled some people to call them as a new subclass of "Type IIb" SNe, but obviously this is still a controversial problem for further investigation.

5.2 A new subclass of Type II SNe?

Recent observations of some Type II SNe suggest that a new subclass may be needed[29]. The properties that separate these objects from the mass of SN II is that the Hα profiles of them are of two parts, with narrow peaks sitting on broad bases. No P–Cygni component is seen. The centroid of the base is blue–shifted relative to the narrow portion of the profile. Within the uncertainties of the flux calibration, the narrow portion of the line appears to be constant. The narrow portion is likely due to surrounding H II regions. The evolution of the spectrum is slow, with the overall appearance remaining approximately constant for ~50–100 days. This is not the behaviour seen in the prototypical Type II SN 1980K, in SN 1979C or in SN 1987A.

Schlegel (1990)[29] designated these events as SN II n ('n' for narrow) and listed 8 events likely to constitute the subclass, i.e., SN 1978G, SN 1987B, SN 1987C, SN 1987F, SN 1988I, SN 1988Z, SN 1989C and SN 1989L. The most recently observed Type II supernova of this possibly subclass is SN 1994W. Figure 6 shows some spectra of these SNe.

Of the Type II SNe within this subclass three objects need particularly to be mentioned, i.e. SN 1987F, SN 1988I and SN 1988Z. When SN 1987F was first observed it showed broad Hα superposed on a nearly featureless continuum, but its profile did not have the characteristic P-Cygni shape,and its centroid was blue–shifted by $\geq$ 1500 km·s^{-1} with respect to the systematic velocity[30]. Many months later, the object was dominated by broad permitted emission lines of hydrogen, with Fe II and Ca II emission detected as well. However, the forbidden lines, which are normally quite strong at this phase, were very weak. The overall optical spectroscopic properties

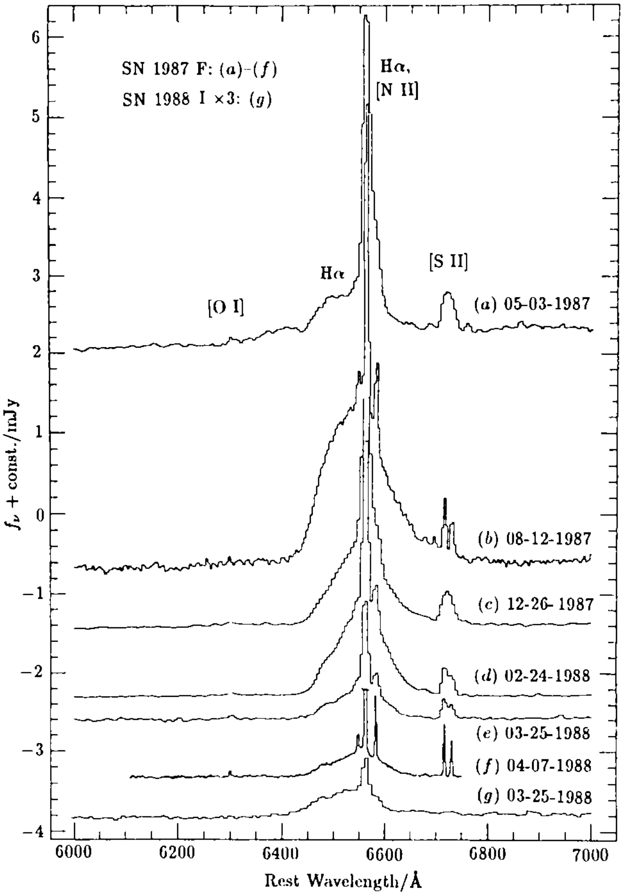

Fig.6 Hα profile in SN 1987F as a function of time, and in SN 1988 I at one epoch.

of SN 1987F closely resemble those of Type 1 Seyfert nuclei and QSOs. The same can be said for Type II SN 1988I which is much less extensively observed , although in this object there is no direct evidence for Fe II emission. Filippenko (1989)[30] suggested that, had either of these SNe occurred in the nucleus of a normal galaxy, the nucleus would probably have been classified as a Type 1 Seyfert if the only data available were low-resolution optical spectra. He suggested that the observed properties of some low-luminosity active galaxies might actually be due to violent bursts of star formation rather than accretion onto a supermassive black hole. SN 1988Z was discussed in detail by Turatto et al (1993)[31]. This relatively bright supernova shows an unusual photometric behaviour, with broad light curves in the B, V and R bands resembling those of SN 1987F. The spectrum is characterized at all epochs by strong Balmer emission , without the usual P-Cygni absorption component which is typical of SN II at early stages. Several He I emission lines are also visible. These lines have a complex structure, with several components evolving with time with respect to both width and intensity. This object is an ideal candidate for a supernova in which there is interaction of the SN ejecta with a circumstellar wind.

5.3 SN 1992am

Schmidt *et al* (1994)[32] presented photometry and spectroscopy of SN 1992am after five months following its discovery.The data showed SN 1992am to be type II-P, displaying hydrogen in its spectrum and the typical shoulder in its light curve. Using the bolometric light curve, they estimated that SN 1992am ejected approximately 0.30 $M_\odot$ of ^{56}Ni, an amount four times larger than that of other well studied SNe II. SN 1992am's host galaxy lies at a redshift of cz = 14600 km·s^{-1}, making it one of the most distant SNe II discovered, and an important application of the Expanding Photosphere Method (EPM). They derived a distance $D = 180^{+30}_{-25}$ Mpc for the host galaxy of SN 1992am using EPM, which is independent of all other rungs in the extragalactic distance ladder. The Hubble constant inferred from this object is $H_0 = 81^{+17}_{-15}$ km·s$^{-1}\cdot$ Mpc^{-1}. In the future, with more of these distant objects, people hope to establish an independent and statistically robust estimate of H_0 based solely on Type II SNe.

6 Conclusions

In this review we first introduce a basic classification scheme for the whole sample of SNe. SNe with H lines in the spectra are classified as Type II, which are further divided into subclasses of SN II–P and SN II–L according to the morphology of their light curves. SNe without H lines in the spectra are classified as Type I, which are further divided into subclasses of SN Ia, SN Ib and SN Ic according to the features of spectra at maximum light.

We then describe progress concerning the spectral observations of each type of SNe. Type Ia SNe, which were believed to be a nearly homogeneous class before, show quite large variations both in photometric and spectroscopic behaviours, so that SNe Ia can be arranged in a sequence, from luminous blue events with enhanced production of iron–peak elements, like SN 1991T, to normal ones like SN 1989B, and then to subluminous red events with underproduced iron–peak elements like SN 1991bg.

Type Ib/Ic SNe are established as a separate category only for a decade, so the sample of SN Ib/Ic is still quite small. Whether hydrogen contaminates the spectra of SN Ic at maximum light is still a controversial question.

Observations of Type II SNe have challenged the classification scheme of SNe. The evolution from Type II SNe at maximum light to Type Ib/Ic SNe at later times for SN 1993J and SN 1987K has impelled people to suggest a new subclass of "Type IIb" SNe. Some other Type II SNe show quite peculiar Hα profiles, with narrow peaks sitting on broad emission bases. The spectra of SN 1987F resemble those of Type 1 Seyfert nuclei. SN 1988Z is an ideal candidate for an SN in which there is interaction of the SN ejecta with a circumstellar wind. The host galaxy of SN 1992am lies at a redshift cz = 14600 km·s^{-1}, making SN 1992am one of the most distant SNe II discovered. The Hubble constant inferred from the observations of SN 1992am is $H_0 = 80^{+17}_{-15}$

km·s^{-1} · Mpc^{-1}.

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