Statistical Analysis of Supernovae and the Progenitors of SN Ib and SN Ic

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We review the fundamental classification scheme and statistical analysis of supernovae, emphasizing recently introduced subtypes, SN 1987K, and SN 1993J. Type Ib/Ic and Type II supernovae are of interest for starburst galaxies. We discuss possible progenitors of SN Ib and SN Ic, and the possibility that they may be Wolf-Rayet stars.

1. Introduction

Up to May 1, 1993, 890 supernovae have been discovered, of which 480 have been classified. Today, with data of increasing quantity and precision, we have categorized supernovae into several groups, not just Types I and II, but Types Ia, Ib/Ic, II-L, IIp, 87A, and probably more to come. But, except for SN IIp and SN 1987A, we are still unclear as to the evolution of the progenitor star (or stars). As the rich diversity of supernovae becomes more evident, we are increasingly challenged to ask: what are the stellar progenitors and the explosion mechanisms of the various types and subtypes of supernovae? What makes a SN Ia and what would a progenitor system look like? Are the progenitors of SN Ib/Ic all Wolf-Rayet stars? Here we attempt a brief overview of these questions. For more extensive discussions of issues bearing on supernova progenitors, see recent reviews by Wheeler(1990, 1991) and Branch *et al.* (1990).

We have reached a basic understanding of how the observable properties of SNe depends on the characteristics of the immediate presupernova stars and their explosion parameters. The observed sites (galaxy morphological classes and locations within galaxies) of a supernova type are related to the initial masses of the stellar progenitors. The more massive the progenitors, the more closely the SNe will be associated with regions of recent star formation. Supernova rates are determined by the progenitor initial mass function and by the fraction of such stars that has the requisite binary characteristics. Massive stars are more rare than low mass stars. To predict what kinds of SNe the progenitors will produce, we need to specify the states of the core and the envelope of the presupernova star, the explosion mechanism, and the density of the circumstellar shell. In §II, we discuss the present classification of supernovae. §III is devoted to the statistical analysis of supernovae, §IV is concerned with the progenitors of SN Ib/Ic. The relationship of starburst galaxies Wolf-Rayet stars with supernovae is presented in §V and §VI.

2. Classification of Supernovae

The fundamental classification scheme for supernovae is based on their spectra. As we learn more the scheme becomes more complex; perhaps every supernova is unique in some aspect. Harkness & Wheeler (1990) give an updated summary of supernova spectral classifications.

Almost all of the observed Type II supernovae (SNe II) have been found in spiral galaxies and are associated with both spiral arms and HII regions. A safe generalization is that SNe II come from massive stars.

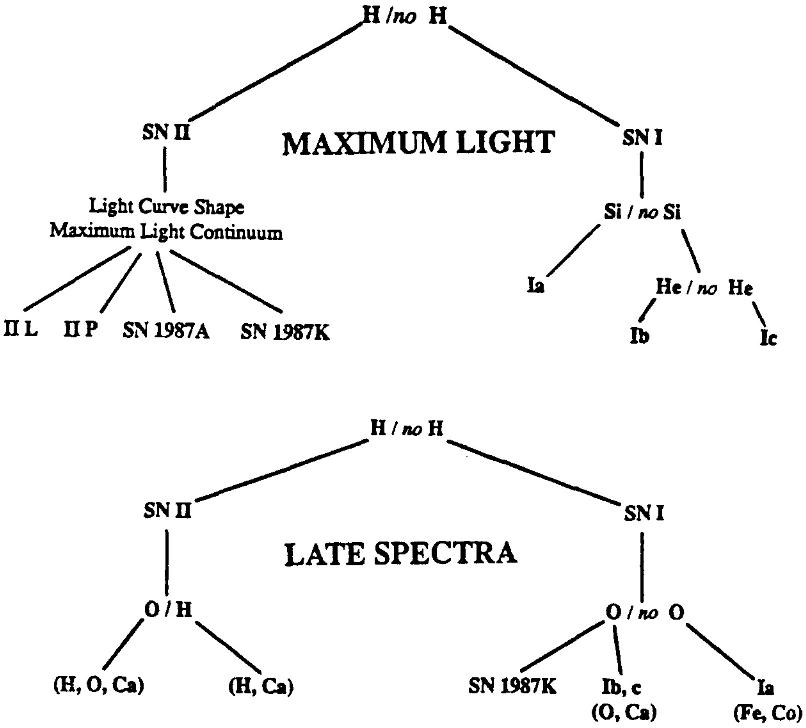

FIGURE 1. Classification scheme for supernovae based on spectral features at maximum light and at late (6 months supernebula) times (Harkness & Wheeler 1990)

2.1. *SNe I and SNe II at Maximum Light*

Figure 1 shows the basic classification scheme. The class of a supernovae has traditionally been determined by its spectrum near maximum light. The basic distinguishing property was whether or not the spectrum showed evidence of hydrogen. If so, the event was classified as Type II; if not, Type I. Among SNe II a further distinction has been proposed based on the shape of the light curve. Those with a pronounced plateau are called Type II plateau (SN II-P), and those that have a nearly linear decline in magnitude after peak light are called Type II linear (SN II-L). With the advent of SN 1987A we now must add a third sub-class. The light curve of SN 1987A was very different, evidently because its progenitor was a compact blue star, although its exponential tail resembles that of SNe II-P. It has been suggested that Type I supernova should be sub-classified according to features of the spectra. One key is the presence or absence of the strong SiIIλ6150 P-Cygni absorption feature. Classical Type Ia events show this feature. Those that do not have come to be known as a separate subclass. The events that show no SiIIλ6150 near maximum light, but do show HeIλ5876, are identified as SN Ib. Wheeler & Harkness (1991) proposed the category SN Ic for these events and then presented atmosphere models suggesting that SN Ib and the candidates for SN Ic might be similar except for the relative concentrations of He in the envelope. These SN Ic events are probably physically closely related to the SN Ib events. We can expect that increasing physical understanding and gradations of properties will ultimately supplant the purely empirical classification schemes.

2.2. *Late-time Nebular Spectra*

In recent years we have seen a great deal of work and new insight into the nature of supernova spectra during the nebular phase. This phase begins roughly six months after maximum, when the photosphere recedes, densities drop, and the spectrum becomes dominated by nebular emission lines. Most nebular spectra preserve the distinction of SN I or SN II as defined by the early-time spectra. Events with H lines near maximum light also show strong Balmer line emission during the nebular phase. Some events show also strong [OI]$\lambda\lambda$6300, 6364 emission as well as hydrogen recombination lines and permitted and forbidden CaII lines. It is not clear whether SN Ic events show identifiable differences from the SN Ib events during the nebular phase.

2.3. *SN 1987K*

It remains an interesting question to determine where SN 1987K fits in the classification and physical scheme of supernovae. Near maximum light, SN 1987K was apparently a Type II from the taxonomical definition that such events show hydrogen in the spectrum. At late times, however, its spectrum was indistinguishable from that of a Type Ib (or Ic) and definitely did not resemble that of a SN II nor a SN Ia. The late-time spectrum suggests that its progenitor was a massive star, given the preponderance of circumstantial evidence that SN Ib events arise in the cores of massive stars. Filippenko (1989) has challenged the standard classification scheme of supernovae with his data on SN 1987K. The most obvious explanation for the SN 1987K phenomenon, that it has a thin outer envelope of hydrogen, does not work. The calculations described above to check the SN Ib model were motivated in part by SN 1987K. Why this event differs from other SN II events is not clear. We need detailed models to understand possible explanations of the differences in spectrum evolution.

2.4. *SN 1993J*

SN 1993J in M81 is providing us with a wealth of new and unique information on the progenitor evolution and explosion mechanism. It was identified as a SN II from hydrogen lines in its early spectrum. But the light curve of SN 1993J is atypical for this class of supernova, with the intensity rising to a second maximum after the initial outburst. The light curve around the second maximum more closely resembles that of the Type Ib SN 1983N. Nomoto *et al.* (1993) suggest that the progenitor lost most of its envelope by mass transfer to a binary companion. A K0 supergiant has been suggested as a possible progenitor of SN 1993J. The detection of X-rays (Tanaka 1993) and radio (Pooley & Green 1993) from SN 1993J are consistent with the idea that the progenitor was a red supergiant with a substantial amount of circumstellar gas. The asymmetry of SN 1993J inferred from the polarization (Trammell *et al.* 1993) and line features (Hu *et al.* 1993) suggest that SN 1993J is a Type IIb supernova that evolved from a binary progenitor. Baron *et al.* (1993) present spectra of SN 1993J, which show strong hydrogen Balmer lines with pronounced P-Cygni profiles. Two groups at Beijing Astronomical Observatory (BAO) have been monitoring SN 1993J continuously from April to July 1993. Zhou *et al* (1993) have conducted UBVRI photometry on the 60 cm Telescope, while Wang *et al.* (1993) have obtained spectroscopic data at the BAO's 2.16 meter telescope. The time evolution of the various absorption and emission lines indicates that the supernovae debris is not spherically symmetric (see Fig.2). The most recent spectra (Wang *et al.* 1993) show that the oxygen lines are blueshifted by about 1775 km/sec .

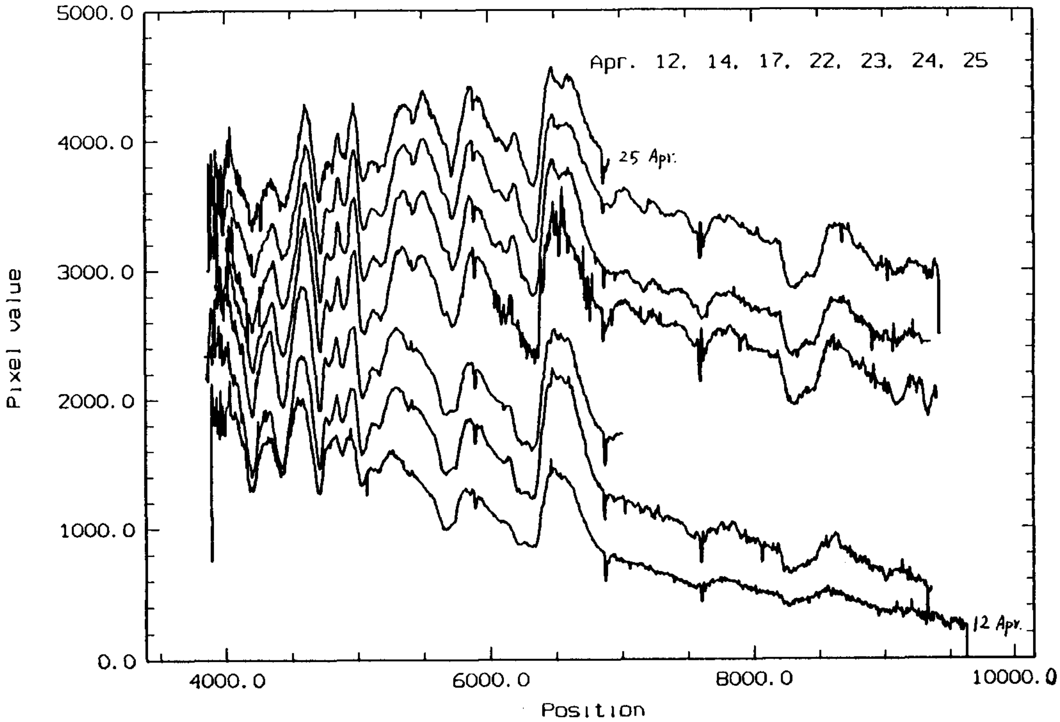

FIGURE 2. The early optical spectrum of SN 1993 J

3. Statistical Analysis of Supernovae

3.1. *Correlation of Supernova Types with Galactic Morphological Types*

The Asiago supernova Catalogue (Turatto 1993) presents data for 890 SNe. We surveyed these data (updated to SN 1993J) and analyzed them statistically. Table 1 shows the frequency distributions of various types of classified supernovae with respect to the different morphological types of their parent galaxies (the label nc means that the objects lack classification).

3.2. *Supernova Rates*

Clues to the origin of supernovae are found in their rates of occurrence in various types of galaxies. SN Ia are associated with old stellar populations; SN II and SN Ib are associated with young populations. For 736 galaxies surveyed, which have produced 51 supernovae, Cappellaro and Turatto (1988) have calculated control times, making allowance for an inclination effect, to estimate the rate of supernovae. Evans & van den Bergh (1989) have surveyed a sample of 855 Shapley-Ames galaxies, in which 24 supernovae occurred during 1980-1988. They calculated control times for SN Ia, SN Ib and SN II in different galaxy-type bins to infer the rate of supernovae frequencies. Van den Bergh & Tammann (1991) give the adopted supernova frequencies.

3.3. *Multiple Supernovae in Spiral Galaxies*

Because supernovae are rare, independent events, the relation of N(SNe) and N(galaxies) should follow a Poisson distribution. However, Guthrie (1990) found that the apparent frequency distributions of multiple supernovae in spiral galaxies is not a Poisson distribution. We (Li & Li 1993) have taken into account the following effects: Hubble types of

TABLE 1. Supernova Types with Galactic Types

	Ia,I	Ib/c	all I	II	Others	nc	total	
E	16	-	16	-	-	29	16	45
SO	19	2	21	-	-	17	21	38
SOa	3	-	3	1	-	1	4	5
Sa	12	1	13	5	1	31	19	50
Sab	4	-	4	6	1	10	11	21
Sb	21	3	24	15	-	63	39	103
Sbc	20	4	24	12	-	31	36	67
Sc	28	14	42	44	6	78	92	170
Scd	7	-	7	17	1	5	25	30
Sd	4	-	4	3	-	2	7	9
Sdm	2	-	2	1	-	2	3	5
Sm	1	1	2	1	-	2	3	5
S	11	-	11	3	-	62	14	76
I0	8	-	8	-	-	1	8	9
Im	-	1	1	1	-	1	2	3
I	-	-	-	1	1	22	2	24
nc	86	4	90	42	-	79	132	211
Total	242	30	272	152	12	445	436	881

galaxies, luminosity, inclination, distance. The sample of 667 galaxies comes from RC2, with some information from the UGC redshift catalogue of galaxies. With a sample of 169 supernovae, updated to Dec 31, 1992, we found that the frequency distribution of multiple SNe in spiral galaxies is still non-Poissonian. Perhaps star formation plays an important role (see §V). We have calculated the radial distributions of supernovae in galaxies that have hosted one, two, three, or four SNe and have used the K-S test to see whether they can belong to the same sample. We found that the radial distributions are not the same. Probably, galaxies with three or more SNe come from a sample of galaxies that are in a starburst phase.

4. Progenitors of Type Ib Supernovae

Recently, there has been a spate of interest in SNe Ib, because of: (1) the independent observations of peculiar infrared light curves among SNe I; and (2) the realization that the optical spectra of SNe Ib differ from those of most SNe I. For a supernova to be classified as a SN Ib, its spectrum must: (1) lack hydrogen emission and absorption lines at all times, as with SNe Ia (Porte & Filippenko 1987); (2) generally resemble the spectra of SNe Ia during the first few months past maximum, except that it must lack the SiIIλ6150 absorption trough 25 days after maximum; (3) exhibit strong [OI]$\lambda\lambda$6300 and [CaII]$\lambda\lambda$7300 emission.

The characteristics of SNe Ib can be summarized as follows (Panagia & Laidler 1991):

- The 6150Å feature is absent from the spectrum;
- The overall spectral distribution is redder and fainter (~ 1.5 magnitudes) than for SNe Ia;
- The optical light curve is essentially "normal," similar to that of SNe Ia;

- The IR light curve is single peaked, the maximum occurring a few days after the optical maximum;
- They are strong radio emitters with a steep spectrum and a quick temporal decline;
- They are found only in spiral galaxies; and
- They are located in spiral arms, often near an HII region.

Branch (1988) discussed the origin of SNe Ib. Supernovae observed during their photospheric phases display three distinct kinds of spectra: Type II, which by definition show optical hydrogen lines; Type Ia, which have neither hydrogen nor helium lines; and Type Ib, which have helium but not hydrogen lines. However, we should consider four distinct chemical compositions of the outer layers of exploding stars: (1) hydrogen-rich, or, speaking loosely, "solar"; (2) helium-rich, or, loosely, "Wolf-Rayet"; (3) deflagration – initially, a mixture of heavy elements from carbon to radioactive nickel (which decays through cobalt to iron); and (4) detonation – initially a mixture of just helium and radioactive nickel. Three fundamental constraints on the nature of SNe Ib are: (1) the presence of strong optical lines of HeI during the photospheric phase; (2) the presence of strong forbidden lines of oxygen ions during the nebular phase; and (3) the association with regions of recent star formation. These constraints point immediately to the possibility that SNe Ib result from the collapsing cores of massive stars that have lost their hydrogen envelopes, i.e., Wolf-Rayet stars. Alternatively, SNe Ib may result from a thermonuclear explosion in an accreting white dwarf. It is not obvious which (if either) of these two models really produces SNe Ib.

SNe Ic resemble SN Ib spectroscopically, except that HeI lines are weak or absent at early times. Thus SNe Ic are sometimes called "helium-poor" SNe Ib. To clearly identify the progenitors of SNe Ib/Ic, it is necessary to compare the observed bolometric (UV to IR) light curves with theoretical models. Jeffery *et al.* (1991) concluded that a helium star model for SN Ic is adequate and slightly favored for explaining the spectrum of the Type Ic SN M near maximum. Evidence continues to accrue that while SNe Ib/Ic are linked, SNe Ib can be distinguished from SNe Ic. All the well-established light curves of SNe Ic seem to decline rather rapidly, suggesting small ejecta masses, while SN Ib events seem to have rather large ejecta masses (Wheeler *et al.* 1993).

5. Supernovae in Starburst galaxies

A starburst galaxy is one with a region of strong star formation, including massive stars, the deaths of which are expected to result in supernovae. An example is the nuclear region of M82, for which Rieke *et al.* (1980) have estimated a supernova rate of 0.3/yr. SNe II and SNe Ib both show a clear correlation with HII regions and with star formation rates in galaxies. Chevalier (1991) discussed supernovae and supernova remnants in starburst galaxies, and Richmond & Filippenko (1991) presented the results of searches for supernovae in starburst galaxies. SNe Ib and SNe II are of special interest for starburst galaxies because they are thought to have massive progenitors. SNe II generally have red supergiant progenitors (SN 1987A being an exception), while SNe Ib's have more compact progenitors and often show radio emission indicating dense circumstellar matter. We believe that they are massive stars which have lost their hydrogen envelopes prior to the explosion.

Terlevich *et al.* (1991) extended TM85 to include the supernova phase in the evolution of the nuclear starburst. According to the initial mass of the progenitor, two different supernova phases are expected. The first is a SN Ib phase at the end of life-time of the most massive stars ($M > 25 M_\odot$). These SNe have Wolf-Rayet progenitors; they are

TABLE 2. Type Ib and Ic Supernovae

SN	M_{MAX}	Type	Galaxy	Galaxy Class
1954A	9.8	Ib	NGC4214	Im
1962L	14.0B	Ib	NGC1073	SBc
1964L	13.4	Ib	NGC3938	Sc
1969J	11.4B	Ib	NGC3198	SBc
1975B	15.5	Ib	Anon0316+41	So
1976B	15.2B	Ib	NGC4402	Sc
1982R	14.8B	Ib	NGC1187	SBc
1983I	13.7B	Ib	NGC4051	SBc
1983N	11.6	Ib	NGC5236	SBc
1983V	13.5	Ib	NGC1365	SBb
1984L	14.0B	Ib	NGC991	Sc
1985F	12.1B	Ib	NGC4618	SBm
1986M	16.5	Ib	NGC7499	SAo
1987M	15.0	Ib	NGC2715	Sc
1988L	16.5	Ib	NGC5480	Sc
1989E	18.6B	Ib	MCG+5-32-45	?
1990B	16.0V	Ib	NGC4568	Sbc
1990I	15.6V	Ib	NGC4650A	Sm
1990U:	16.0B	Ic	NGC7479	Sc
1990W:	15.0V	Ic	NGC6221	Sc
1990aa	17.0CCD	Ic	U540	Sc
1990ai	19.0pg	Ibc	0 117+2159	?
1990aj	18.5V	Ib	NGC1640	Sb
1991A	17.0V	Ib	IC2973	Sc
1991K	18.0R	Ib	NGC2851	?
1991L	18.0R	Ibc	MCG+7-34-134	?
1991N	15.0CCD	Ibc	NGC3310	Sbc
1991R	18.0J	Ibc	1552+1907	?
1991ar	17.0J	Ib	IC49	Sc
1992K	16.2V	Ic	ESO269-G57	Sab

predicted to be optically dim and radio loud, and to produce remnants similar to Cas A. During this first phase the starburst should have a spectrum resembling that of a typical Seyfert 2 and should display substantial radio emission. During the second phase, SNe II emission should mark the end of the life-times of intermediate mass ($5M_\odot < M < 25M_\odot$) stars. These SNe have red supergiant progenitors. The SN ejecta will presumably interact with dense circumstellar/interstellar medium. During this phase the spectrum of the starburst should look like that of a Seyfert 1 or QSO.

6. Wolf-Rayet Stars and Supernovae

In the Milky Way, there are 172 known Wolf-Rayet stars (van der Hucht *et al.* 1991), of which 91 are classified as type WN, 73 are WC, 6 are WN/WC, and 2 are WO. Nomoto (1991) discussed the possible connections between Wolf-Rayet stars and type Ib/Ic/IIb supernovae and concluded that typical SNe Ib/Ic are the explosions of $3 - 5\ M_\odot$ helium stars in close binary systems. The low masses are required to successfully model the peak luminosities and rapid decline of the light curves of SNe Ib/Ic. Are Wolf-Rayet stars the progenitors of type Ib/Ic supernovae? Filippenko (1991) discuss evidence for and against the hypothesis that SNe Ib/Ic are produced by core collapse in a massive evolved progenitor. SNe Ib/Ic probably do represent the explosions (core collapse) of hydrogen-deficient massive stars. However, the question of whether most of these are Wolf-Rayet stars is far from settled.

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