REVIEW ON THE OBSERVED AND PHYSICAL PROPERTIES OF CORE COLLAPSE SUPERNOVAE

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Abstract
Core collapse supernovae prove to comprise the most common general class of exploding star in the Universe and they come in a great variety of flavors. The wide range of luminosities, expansion velocities, and chemical abundances displayed by these objects is evidence for large variations in explosion energy and in the properties of their progenitors. This paper summarizes observed and physical properties of all types of core collapse supernovae. Despite the great diversity displayed by these objects, several regularities emerge which suggest that 1) there is a continuum in the properties of these objects, 2) the mass of the envelope is one of the driving parameters of the explosion, or it is correlated with some other property of the core, with the latter determining the outcome of the explosion, and 3) the physics of the core and explosion mechanism of all core collapse supernovae are not be fundamentally different, regardless of the external appearance of the supernova. Far above in energy scale and $^{56}$Ni production lies SN 1998bw, the only supernova firmly associated with a gamma-ray burst.

Keywords: supernovae, nucleosynthesis, abundances

Introduction
Supernovae (SNe) owe their name to astronomers Baade and Zwicky who, in the 1930’s, realized that these objects were much more luminous and rarer than common novae (Baade 1938; Zwicky 1938). Their high luminosities (comparable to that of their host galaxies) and broad spectral lines led them to conclude that SNe were very energetic explosions. They went a step further and hypothesized that a SN resulted from the “transformation of an ordinary star into a collapsed neutron star”, a remarkable idea for its time which lies at the heart of modern models for SNe that result from the gravitational collapse of the cores of massive stars.

“Core collapse SNe” (CCSNe, hereafter) prove to comprise the most common general class of exploding star in the Universe (Cappellaro et al. 1999), each releasing $10^{51}$ ergs of mechanical energy and enriching the interstellar
medium with several solar masses of new chemical elements. Their astrophysical importance is no longer limited to the central role they play in the chemical evolution of the Universe and in the shaping of the galaxies themselves, but now extends to the possibility that a fraction of them might be the source of the enigmatic gamma-ray bursts (GRBs).

CCSNe come in a great variety of flavors. In this paper, I summarize the photometric and spectroscopic properties of all types of CCSNe and their physical parameters. Despite the great diversity displayed by these objects several regularities emerge which provide valuable clues and a better insight on their explosion mechanism, a matter that still remains quite controversial (see Janka et al. 2003, Cardall 2003, and Burrows 2000 for recent reviews).

1. Supernova Classification

Observers classify SNe according to the presence or absence of certain elements in their atmospheres based on spectroscopic observations. By the time Baade and Zwicky introduced the SN class, spectra of these objects had already been obtained. Minkowski (1941) published the first paper on this subject where he introduced two main SN spectroscopic types: the Type II class comprises SNe with prominent hydrogen lines, whereas the Type I class is defined by the absence of hydrogen in their spectra. This classification scheme has evolved as more spectra have become available (see Filippenko 1997 for a detailed review). Five distinct SN types can be distinguished from spectra obtained near maximum light (Fig. 1):

   classical Type II: These objects have prominent Balmer lines exhibiting P-Cygni profiles.

   Type IIdw: The members of this class have strong hydrogen lines in emission. They can be distinguished from the classical Type II SNe by the lack of absorption in their Balmer lines. Chugai (1997a) introduced this designation to reflect the fact that these SNe undergo significant interaction with a “dense wind” produced by the SN progenitor prior to explosion.

   Type Ia: They are characterized by a strong absorption attributed to Si II 6347,6371.

   Type Ib: These objects are distinguished by spectra with no evident Balmer lines, weak or absent Si II 6347,6371, and strong He I 4471, 5876, 6678, and 7065 lines. Bertola (1964) reported the first observations of this class of SNe but the “Ib” designation was introduced later by Elias et al. (1985).

   Type Ic: The members of this class are characterized by weak or absent hydrogen and helium lines, and no evident Si II 6347,6371. They show Ca II H&K in absorption, the Ca II near-IR triplet with a P-Cygni profile, and O I 7774 in absorption. The “Ic” class was introduced by Wheeler & Harkness (1986).
During the past years a new class of SN seems to be emerging, which is characterized by a smooth and featureless spectrum at early epochs. The current interpretation is that these objects have the usual lines observed in SNe Ic but with an extreme Doppler broadening caused by unusually high expansion velocities. There are three members of this class (SN 1997ef, SN 1998bw, and SN 2002ap), which are often called “hypernovae” or SNe IId. One of them (SN 1998bw) proved to be a remarkable event because it was found at the same temporal and spatial location as GRB980425 (Galama et al. 1998). In the rest of this paper I will refer to these objects as Type Ic hypernovae to reflect the observational fact that their expansion velocities are unusually high.

SNe II, Ib, and Ic occur near star forming regions and have never been observed in elliptical galaxies, which leads to the idea that their progenitors are massive stars born with more than $8 \, M_\odot$ that undergo core collapse, leaving a neutron star or black hole as a remnant and launching an explosion of their envelopes. Type Ia SNe, on the other hand, are observed in all types of galaxies. Given their lack of hydrogen, it is thought that they arise from white dwarfs that explode as they approach the Chandrasekhar mass ($1.4 \, M_\odot$) after a period of mass accretion from a binary companion, leaving no compact remnant behind them.
Theorists give less importance to the external appearance of SNe (spectra) but to their hearts (the origin of the explosion), and distinguish two fundamentally different SN types regardless of their spectroscopic appearance: core collapse and thermonuclear SNe. In this sense SNe Ib and SNe Ic are thought to be physically much closer to SNe II than to SNe Ia, even though SNe Ia, Ib, and Ic all share the same prefix (owing to the lack of hydrogen in their atmospheres).

2. The Properties of Core Collapse Supernovae

Stars born with $8-10 \, M_\odot$ can reach temperatures and densities sufficiently high to produce O/Ne/Mg cores. More massive stars can proceed even further and end up with Fe nuclei. When nuclear burning ceases in these stars the core becomes unstable and gravitational collapse follows, leading to the formation of a neutron star or black hole. It is thought that this is the place where a supernova is launched, but the mechanism by which the core implosion triggers the explosion of the stellar mantle still remains a difficult theoretical problem (see Janka et al. 2003, for example). The standard paradigm is that most of the gravitational energy released during the collapse is carried away by neutrinos ($10^{53}$ ergs) and that a small fraction (1%) of this energy is deposited in the bottom of the star’s envelope. This produces a shock wave that propagates through the interior of the star and emerges on the surface a few hours later. This is a generic model for CCSNe, whose optical luminosities comprise only a small fraction of the energy released by the gravitational collapse, and whose optical spectra vary solely by the ability of their progenitors to retain their H-rich and He-rich envelopes prior to explosion and/or by the density of the medium in which they explode. In what follows I proceed to discuss the properties of all spectroscopic types of CCSNe.

2.1 Classical Type II Supernovae

These SNe are thought to have massive progenitors with extended H-rich envelopes that undergo little interaction with the circumstellar medium (CSM). They are characterized by optical spectra dominated by Balmer lines exhibiting P-Cygni profiles. Many of these SNe have been aimed with radio telescopes, yet only a handful of nearby events such as SN 1987A and SN 1999em have been detected at these frequencies (Weiler et al. 2002). The low radio luminosity of these objects implies that they explode in low-density environments. Based on the LOTSS (Li et al. 2000) discoveries reported to the IAU Circulars in 2001, I estimate that classical SNe II constitute 45% of all CCSNe.

Figure 2 displays optical spectra of a sample of classical SNe II taken 60 days after explosion. The most prominent feature of these objects is H exhibiting a P-Cygni profile, which is characteristic of an expanding atmosphere
Figure 2. Optical spectra of classical Type II SNe obtained 60 days after explosion, sorted by the width of their spectral lines. The spectrum of SN 1987A is from Phillips et al. (1988), that of SN 1999em is from Leonard et al. (2002a), and the rest are from Hamuy (2001).

(Kirshner & Kwan 1974; Jeffery & Branch 1990). Besides the Balmer series these spectra show strong Ca H&K, Na I D, and Fe lines. Clearly this sample of SNe reveals a great degree of individuality. In particular it is possible to observe a wide range in the line widths, from the “narrow-line” SN 1999br to the “broad-line” SN 1992am, which suggests a significant range in expansion velocities.

A sample of absolute $V$ lightcurves of classical SNe II is shown in Fig. 3. SN 1999em is among the best observed objects of this class which is characterized by a long plateau (~110 days) of nearly constant luminosity. The plateau is followed by a sudden drop in luminosity and a linear tail with a slope of $0.01 \text{ mag day}^{-1}$. The plateau corresponds to the optically thick phase in which the SN has a well-defined photosphere. Since the opacity is dominated by electron scattering, the photosphere lies at the shell where H recombines. As the ejecta expands a recombination wave recedes through the envelope. The end of the plateau corresponds to the time when the photosphere reaches the He-rich envelope. Owing to much lower opacities the photosphere recedes faster and the luminosity drops promptly until the SN becomes transparent. Up to this point the lightcurve is powered primarily by the internal energy of the SN previously deposited by the shock wave that ensued from core collapse. During
Figure 3. Absolute $V$ lightcurves of classical Type II SN. The observations are from Hamuy & Suntzeff (1990) for SN 1987A; from Hamuy (2001) for SN 1992am and SN 1999br; and from Suntzeff et al. (2003) for SN 1999em.

the nebular phase, on the other hand, the lightcurve is powered by the radioactive decay of $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, at a rate corresponding to the e-folding time of the $^{56}\text{Co}$ decay (111.26 days). $^{56}\text{Co}$ is the daughter of $^{56}\text{Ni}$ (with a half-life of 6.1 days), so the luminosity of the tail is determined by the amount of $^{56}\text{Ni}$ freshly synthesized in the explosion. Plateau SNe (SNe II-P) such as SN 1999em comprise the vast majority of spectroscopically classical SNe II. This photometric class was first identified by Barbon et al. (1979). Two more examples are shown in Fig. 3: SN 1999br and SN 1992am. It is evident that there is a great range (~5 mag) in luminosity within this group.

SN 1987A is the most well-observed SN to date and its lightcurve (Fig. 3) proves clearly different than that of SNe II-P. It is characterized by a steady rise during three months. After maximum light the SN displayed a fast decline phase of 20 days, followed by a linear tail at the rate expected for $^{56}\text{Co}\rightarrow ^{56}\text{Fe}$. Its peculiar shape has been attributed to the relatively small radius of its blue supergiant progenitor Sk 202-69 (Woosley et al. 1987). Unlike SNe II-P which explode as red supergiants (Arnett 1996), most of the shock deposited energy in SN 1987A went into adiabatic expansion, thus leading to a dimmer plateau and to a lightcurve promptly powered by $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ (Blinnikov et al. 2000). The lightcurve shape of SN 1987A reflects the combination
of an ever decreasing deposition rate with an ever increasing escape probability for the photons from the SN interior as the ejecta gets thinner. SN 1998A (Woodings et al. 1998) and SN 2000cb (Hamuy 2001) are two other clear examples of events with SN 1987A-like lightcurves and, hence, with blue supergiant progenitors. The relatively compact progenitors of these SNe have been attributed to low metallicities and to mass loss to a binary companion prior to explosion.

Figures 2 and 3 suggest that SNe with brighter plateaus have higher ejecta velocities, and vice versa. Figure 4 shows expansion velocities versus plateau luminosities for the 24 SNe II-P having sufficient photometric and spectroscopic data (see Hamuy 2003 for details). Despite the great diversity displayed by SNe II-P, these objects show a tight luminosity-velocity correlation. This result suggests that, while the explosion energy increases so do the kinetic and internal energies. In fact, as shown in Fig. 2 of Hamuy (2003), the luminosity-velocity correlation is also present in the theoretical models of Litvinova & Nadezhin (1985) (LN85).

Using the hydrodynamic models of LN85 it is possible to derive physical parameters such as energy (E), ejected mass (M), and initial Radius (R) for SNe II-P. In such models the lightcurve is shaped by these parameters and their
Figure 5. Effect of explosion energy ($E$), ejected mass ($M$), initial radius ($R$), and nickel mass ($Ni$) on the lightcurve of a SN II-P.

Effect on the plateau phase is illustrated in Fig. 5. While the plateau luminosity is particularly sensitive to $E$, its duration depends largely on $M$. The models of LN85 yield specific calibrations for three observables: the plateau luminosity, its duration, and the photospheric velocity, which can be used to solve for $E$, $M$, and $R$. One problem with the LN85 models is that they do not cover a wide range in energy and mass so the results derived from this calibration often involve extrapolating their formulas. Although it is necessary to expand the parameter space explored by LN85 before we can firmly believe this method, in its current form it can still provide useful insights on the nature of these objects. As mentioned above, the luminosity of the radioactive tail can be used to find the mass of $^{56}\text{Ni}$ ($M_{\text{Ni}}$) synthesized in the explosion, assuming that all the $\beta$-rays from $^{56}\text{Co}$ to $^{56}\text{Fe}$ are fully thermalized in the interior. Fig. 6 shows the 13 SNe II-P for which there is sufficient data to perform such analysis.

Table 1 summarizes the resulting parameters and those independently derived for SN 1987A (Arnett 1996), SN 1997D and SN 1999br (Zampieri et al. 2003), which reveals the following.

There is a wide range in explosion energies, from 0.6 to 5.5 foes (1 foe = $10^{51}$ ergs) among classical SNe II.
The ejected masses encompass a broad range between 14 and 56 $M_{\odot}$. Note that, while stars born with more than 8 $M_{\odot}$ can in principle undergo core collapse, they do not show up as classical SNe II. Perhaps they become white dwarfs (Heger et al. 2003) or they undergo significant mass loss before explosion and are observed as other SN spectroscopic types (Chugai 1997a). Note also that stars as massive as 50 $M_{\odot}$, which are expected to have strong stellar winds (Heger et al. 2003), seem able to retain a significant fraction of their H envelope and explode as SNe II, perhaps owing to lower metallicities. Although these results prove interesting, it must be mentioned that the derived masses are quite uncertain because the LN85 calibration only extends up to 16
Table 1. Physical Parameters for Classical Type II Supernovae.

| SN    | Energy | Ejected Mass | Initial Radius | Nickel Mass |
|-------|--------|--------------|----------------|-------------|
|       | (10^{51} ergs) | (\text{M}_\odot) | (\text{R}_\odot) | (\text{M}_\odot) |
| 1969L | 2.3^{+0.7}_{-0.5} | 28^{+11}_{-8} | 204^{+150}_{-88} | 0.082^{+0.034}_{-0.026} |
| 1973R | 2.7^{+0.9}_{-0.7} | 31^{+12}_{-8} | 197^{+128}_{-78} | 0.084^{+0.030}_{-0.018} |
| 1986L | 1.3^{+0.5}_{-0.3} | 17^{+7}_{-5} | 417^{+304}_{-163} | 0.034^{+0.011}_{-0.010} |
| 1988A | 2.2^{+1.7}_{-1.2} | 50^{+6}_{-4} | 138^{+80}_{-62} | 0.062^{+0.032}_{-0.020} |
| 1989L | 1.2^{+0.9}_{-0.5} | 41^{+15}_{-10} | 136^{+118}_{-66} | 0.015^{+0.008}_{-0.005} |
| 1990E | 3.4^{+1.3}_{-0.9} | 48^{+22}_{-15} | 162^{+148}_{-78} | 0.062^{+0.031}_{-0.022} |
| 1991G | 1.3^{+0.9}_{-0.7} | 32^{+16}_{-10} | 126^{+103}_{-61} | 0.129^{+0.053}_{-0.037} |
| 1992H | 3.1^{+1.8}_{-1.3} | 10^{+4}_{-2} | 586^{+312}_{-170} | 0.256^{+0.069}_{-0.089} |
| 1992Am | 5.5^{+2.3}_{-1.5} | 56^{+24}_{-14} | 96^{+100}_{-45} | 0.019^{+0.008}_{-0.005} |
| 1992ba | 1.3^{+0.5}_{-0.4} | 42^{+17}_{-12} | 224^{+136}_{-65} | 0.090^{+0.034}_{-0.014} |
| 1999cr | 1.9^{+0.8}_{-0.6} | 32^{+14}_{-10} | 224^{+136}_{-65} | 0.090^{+0.034}_{-0.014} |
| 1999em | 1.2^{+0.7}_{-0.5} | 27^{+13}_{-10} | 224^{+136}_{-65} | 0.090^{+0.034}_{-0.014} |
| 1999gi | 1.5^{+0.7}_{-0.5} | 43^{+18}_{-14} | 81^{+150}_{-51} | 0.018^{+0.009}_{-0.008} |

**SN from Other Sources**

| SN     | Energy | Ejected Mass | Initial Radius | Nickel Mass |
|--------|--------|--------------|----------------|-------------|
| 1987A  | 1.7    | 15           | 42.8           | 0.075       |
| 1997D  | 0.9    | 17           | 128.6          | 0.006       |
| 1999bk | 0.6    | 14           | 114.3          | 0.0016^{+0.00011}_{-0.00008} |

- From Arnett (1996).
- From Zampieri et al. (2003).

Of some concern is the sharp contrast found between the ejected masses derived from the LN85 calibration for SN 1999gi and SN 1999em and the values independently obtained by Smartt et al. (2001, 2002). Based on upper limits of the luminosities of the progenitors of these two nearby SNe from pre-discovery images and stellar evolutionary tracks, they derived upper mass limits of $9^{+3}_{-2}$ and $12^{+1}_{-1}$ M\odot for SN 1999gi and SN 1999em, which prove at odds with the values of $43^{+24}_{-14}$ and $27^{+14}_{-10}$ M\odot obtained for these objects from the LN85 calibration. Part of the discrepancy might arise from the LN85 calibration, but it could be due also to the distances adopted by Smartt et al. for the SN host galaxies (in fact with the new Cepheid distance to SN 1999em the upper mass limit rises to $200 M\odot$; Leonard 2003), or uncertain stellar evolutionary models for massive stars.

Except for SN 1987A, within the uncertainties the initial radii correspond to those measured for red supergiants (van Belle et al. 1999), which lends support to the view that the progenitors of SNe II-P have extended atmospheres at the time of explosion (Arnett 1996).

The Ni masses produced by these SNe vary by a factor of 100, from 0.0016 to 0.26 M\odot.
Fig. 7 shows $M$ and $M_{\text{Ni}}$ as a function of $E$ for these 16 SNe II. Despite the large error bars, this figure reveals a couple of correlations. First (top panel), the explosion energy appears to be correlated with the ejected mass, in the sense that more energetic SNe eject greater masses. This suggests that the outcome of the core collapse is somehow determined by the mass of the envelope, or that the mass of the envelope is correlated with some property of the core (e.g. mass), with the latter determining the outcome. Second (bottom panel), SNe with greater energies produce more nickel, a result previously suggested by Blanton et al. (1995). This could mean that greater temperatures and more nuclear burning are reached in such SNe, and/or that less mass falls back onto the neutron star/black hole in more energetic explosions.

2.2 Type IIdw Supernovae

A distinct class of SNe II can been identified which, unlike classical SNe II, are believed to be strongly interacting with a “dense wind” produced by the SN progenitor prior to explosion. These SNe have strong radio emission caused by the interaction with the CSM (Chevalier 1998). Models of the radio observa-
tions imply high mass-loss rates $10^{-4} M_{\odot} yr^{-1}$ for their progenitors (Weiler et al. 2002). SNe IIdw comprise 30% of all CCSNe and 40% of all SNe II.

**Figure 8.** Optical spectra of SNe IIdw obtained 3 months after explosion, compared to the classical Type II SN 1999em.

Fig. 8 shows optical spectra for a sample of SNe IIdw, compared to the classical SN 1999em. Evidently these SNe show a strong degree of individuality, but they are unified by the lack of absorption in the Balmer lines. Their spectra are dominated by strong H broad emission (SN 1979C), sometimes with a superposed narrow (FWHM $200 \text{ km s}^{-1}$) emission (SN 1988Z and SN 1997cy). One of most well-observed and recent additions to the IIdw events is SN 1998S (Leonard et al. 2000). When the narrow component is present the SN is classified as IIn (standing for “narrow”; Schlegel 1990). Occasionally a narrow P-Cygni profile can be observed, such as in SN 1994aj (Benetti et al. 1998) and SN 1996L (Benetti et al. 1999), in which case the SN is typed as IId (the “d” stands for “double” profile).

The interaction of the SN envelope and the CSM is very difficult to model. In the models of Chugai (1997a) this collision produces an outer shock wave that propagates in the unshocked CSM, and an inner shock wave that propagates inward through the SN envelope. In between the two shocks is located a cool and dense shell that produces broad emission lines by excitation from the X-rays produced in the inner and outer shocks. Broad emissions are also...
thought to arise in the undisturbed SN ejecta excited by the X-rays. Chugai (1997b) claims that the absence of the absorption component of the H profile observed in classical SNe II is a consequence of the excitation mechanism: while the atmospheres of the classical SNe II are excited by internal energy of the explosion and by radioactivity, SNe IIdw are predominantly excited by the shocks. In these models the narrow emission component in SNe IIdw is thought to originate in the undisturbed photoionized CSM. The narrow P-Cygni profile observed in SNe IId is attributed to the recombined unshocked CSM.

![Figure 9](image-url)

*Figure 9. Absolute $V$ lightcurves of three SNe IIdw, compared to the classical Type II SN 1999em (solid line; Suntzeff et al. 2003). The observations are from Balinskaya et al. (1980), De Vaucouleurs et al. (1981), and Barbon et al. (1982b) for SN 1979C; Turatto et al. (1993a) for SN 1988Z; and Germany et al. (2000) for SN 1997cy.*

The lightcurves of some SNe IIdw are compared to that of the classical SN 1999em in Fig. 9. The strong degree of individuality seen in their spectra is also reflected in their lightcurves. SN 1979C belongs to the photometric class of “linear” SNe introduced by Barbon et al. (1979). SN 1979C displayed a post-maximum decline phase at a rate of 0.04 mag day$^{-1}$ for 100 days, followed by a slower decline tail at 0.01 mag day$^{-1}$. SN 1980K is another clear example of a linear event (Barbon et al. 1982a). SN 1988Z and SN 1997cy, on the other hand, showed very different behaviors. They both faded slowly, at 0.01 mag day$^{-1}$. This rate is not very different than that of the classical plateau
SN 1999em, but the main difference is that this slow evolution in SN 1988Z and SN 1997cy extended for several hundred days.

Despite the great photometric diversity among SNe IIdw, these objects share the property of being generally more luminous than the classical SNe II. This can be appreciated in Fig. 10, which compares the distribution of peak magnitudes of classical and Type IIdw SNe. The high luminosities of Type IIdw SNe constitute another optical signature of the collision of SN envelopes with dense winds, which efficiently converts kinetic energy into light. Often, this mechanism predominates over the usual SN radiation mechanism, thus leading to a powerful optical display (Chugai 1997a).

Table 2 summarizes physical parameters for three SNe IIdw derived from models involving circumstellar interaction. In general these SNe eject less mass than the classical SNe II, between 1-6 \( M_\odot \). The models require large mass-loss rates before explosion. Two of them exploded with normal energies compared to classical SNe II, but one case (SN 1997cy) was much more energetic than any other SN II. Chugai (1997a) proposes that 1) the progenitors of SNe IIdw are stars born with 8-10 \( M_\odot \) that undergo significant mass loss owing to helium shell flashes during the asymptotic red supergiant branch stage, and 2) the large observed diversity among SNe IIdw is due to large variations in the wind density near the SN progenitor. This hypothesis is consistent with
Table 2. Physical Parameters for Type IIdw Supernovae.

| SN   | Energy (10^{51} ergs) | Ejected M ass (M) | Initial Radius (R) | Nickel M ass (M) | Mass Loss Rate (M yr^{-1}) |
|------|------------------------|------------------|-------------------|-----------------|----------------------------|
| 1979C | 1-2                    | 6                | 6000              | < 0.1           | 1 10^{-4}                 |
| 1988Z | 1                      | < 1              | ...              | ...             | 1-7 10^{-4}               |
| 1997cy| 30                     | 5                | ...              | ...             | 4.0 10^{-4}              |

^a From Blinnikov & Bartunov (1993) and Weiler et al. (2002).
^b From Chugai & Danziger (1994) and Weiler et al. (2002).
^c From Turatto et al. (2000) and Nomoto et al. (2000).

...the conclusions reached above from the LN85 models, that the progenitors of the classical SNe II are born with more than 14 M_sun.

2.3 Type Ib and Ic Supernovae

The distinguishing feature of Type Ib and Ic SNe is the lack of conspicuous hydrogen spectral lines. Their progenitors are thought to be massive stars that lose most of their H-rich (and perhaps their He-rich) envelopes via strong winds or transfer to a binary companion via Roche overflow. Evidence for this hypothesis has been recently revealed by the Type Ic SN 1999cq, which showed intermediate-width helium emission lines caused by the interaction of the SN ejecta with an almost pure helium wind lost by the progenitor (Matheson et al. 2000). Type Ib and Ic SNe are as radio loud as SNe IIdw, yet the mass-loss rates of their progenitors are lower, between 10^{-5}-10^{-6} M_{\odot} yr^{-1} (Weiler et al. 2002). Approximately 25% of all CCSNe fall in the SNe Ib and SNe Ic category.

Fig. 11 shows near-maximum optical spectra of various members of the Type I core collapse family. SN 1984L is one of the prototypes of the Type Ib class, which is characterized by strong He I 4471, 5876, 6678, and 7065 lines. These objects are not seen very often and comprise only 1% of all CCSNe. SN 1987M was the first well established member of the Ic family and SN 1994I proves to be one of the best observed objects of this class. The strongest lines are the Ca II H&K and O I 7774 absorptions, and the P-Cygni profile of the Ca II IR triplet.

Significant effort has been put over recent years into determining the presence of helium in the spectra of SNe Ic in order to better understand the nature of these objects. Recently Matheson et al. (2001) compiled and analyzed a large collection of spectra of SNe Ib and Ic obtained at Lick Observatory. This study showed no compelling evidence for He in absorption in the spectra of SNe Ic and no gradual transition from the Ib to the Ic class, which supported...
the idea that these objects are produced by different progenitors. By contrast, a closer look at the SN 1994I spectrum suggests deeper troughs at the wavelengths of the He I lines, especially at 4471, 4921, and 5876 Ang (Filippenko et al. 1995; Clocchiatti et al. 1996b). The spectrum of SN 1999ex shown in Fig. 11 reveals unambiguous evidence for He I absorptions of moderate strength in the optical region, thus suggesting the existence of an intermediate Ib/c case and a link between the Ib and Ic classes.

The presence of hydrogen in SNe Ib has been recently analyzed by Branch et al. (2002) by comparison to synthetic spectra. Their conclusion is that the 6300 Ang absorption feature seen in the Type Ib SN 1954A, SN 1999di and SN 2000H is H, and that hydrogen appears to be present in SNe Ib in general. A similar analysis led Branch (2002) to conclude that H is also present in the spectrum of the intermediate Type Ib/c SN 1999ex. The presence of hydrogen in Type Ic SNe, on the other hand, is still questionable.

The spectral models of Branch et al. (2002) show that small optical depths are required to fit the H and He lines and that a mild reduction in the optical depths would make SNe Ib look like SNe Ic. This supports the concept that SNe Ib and SNe Ic are not fundamentally different. Their spectroscopic appearance may not even reflect the physical presence of H or He in their atmospheres but only the way these elements are mixed in the envelopes.
The lightcurves of some of the best observed Type I CCSNe are shown in Fig. 12. Evidently the lightcurves do not follow a single template, yet they share the same common features: a rise during 2-3 weeks, a fast dimming during 30 days, followed by a slow decline phase at a rate significantly greater than that expected for the radioactive decay of $^{56}$Co $\rightarrow$ $^{56}$Fe (shown with a dotted line).

Unlike classical SNe II-P, the early-time lightcurves of SNe I are not powered by shock-deposited energy. This is attributed to the fact that these objects have much more compact progenitors, so that the energy deposited in the envelope by the central collapse is largely spent in adiabatic expansion, which leads to a dimmer and brief plateau (Woosley et al. 1987; Shigeyama et al. 1990). Hence, from the very beginning their lightcurves are powered by radioactive heating. While the peak is determined by the amount of $^{56}$Ni synthesized in the explosion, the width depends on the ability of the photons to diffuse out from the SN interior. The width of the lightcurve is determined by the diffusion time which increases with the envelope mass and decreases with expansion velocity. The early-time lightcurve, therefore, provides useful constraints on the $^{56}$Ni mass, envelope mass, and kinetic energy (Arnett 1996). The great range in peak luminosities and lightcurve widths displayed by SNe I suggests a wide
range in mass, velocity, and $^{56}$Ni. The late-time decline rate reveals that a fraction of the $\gamma$-rays from $^{56}$Co ! $^{56}$Fe escape from the SN ejecta without being thermalized and, therefore, can be used to quantify the degree of $^{56}$Ni mixing in the SN interior. In the next section I summarize the physical parameters for these objects.

### 2.4 Type Ic Hypernovae

In the past five years three SNe (SN 1997ef, SN 1998bw, and SN 2002ap) have been found to display very peculiar spectra compared to the standard types described above. Since they show an overall similarity to each other, they seem to define a new spectroscopic class of SNe.

![Maximum-light optical spectra of the three Type Ic hypernovae, compared to the normal Type Ic SN 1994I.](image)

Their maximum-light spectra are shown in Figure 13 along with the normal Type Ic SN 1994I. Their main characteristic is that they are extremely smooth and featureless. They do not show obvious signatures of hydrogen or helium. The few spectral features displayed by these SNe are very broad and hard to identify without spectral modeling. The comparison with SN 1994I suggests that these weird SNe are Type Ic events but with higher than normal expansion velocities. This would lead to significant Doppler broadening and blending of the spectral lines and, hence, to featureless spectra. Judging
from the line widths the velocities increase from SN 2002ap, to SN 1997ef, and SN 1998bw. Their unusual expansion velocities suggest that these objects are hyper-energetic so they are collectively called “hypernovae”. Some people prefer to call them Type IId events.

![Figure 14](image_url)

*Figure 14.* Absolute $V$ lightcurves of the three Type Ic hypernovae, compared to the normal Type Ic SN 1994I (solid line). The observations are from Garnavich et al. (1997a) and Garnavich et al. (1997b) for SN 1997ef; Galama et al. (1998), McKenzie & Schaefer (1999), Sollerman et al. (2000), and Patat et al. (2001) for SN 1998bw; and Gal-Yam et al. (2002) for SN 2002ap.

The absolute $V$ lightcurves of the three hypernovae are shown in Fig. 14 along with the normal Type Ic SN 1994I (solid line). They all share the generic shape of normal SNe Ib and SNe Ic and, like these objects, the hypernovae show great dispersion in lightcurve widths and luminosities. While both SN 1997ef and SN 2002ap showed normal luminosities, the former had a broad lightcurve and the latter evolved much faster. SN 1998bw showed a slow luminosity evolution and was clearly overluminous compared to the other Type Ic events, which suggests a large $^{56}$Ni production.

SN 1998bw was not only remarkable for its great expansion velocities and luminosity, but also because it exploded at nearly the same location and time as GRB980425 (Galama et al. 1998). No GRBs were detected at the position of the other two hypernovae, on the other hand. Since GRBs could arise in relativistic jets (MacFadyen et al. 2001), it could well be that all hypernovae
produce GRBs and that only observers within a range of viewing angles from
the jet axis can detect them.

Table 3. Physical Parameters for Type Ib and Type Ic Supernovae.

| SN     | Type | Energy | Ejected Mass | Initial Radius | Nickel Mass | Reference        |
|--------|------|--------|--------------|----------------|-------------|-----------------|
|        |      | (10^{51} ergs) | M | (M) | (R) | (M) |
| 1983I  | Ic   | 1.0    | 2.1          | 3.7            | 0.15        | Shigeyama et al. 1990 |
| 1983N  | Ib   | 1.0    | 2.7          | 3.0            | 0.15        | Shigeyama et al. 1990 |
| 1984L  | Ib   | 1.0    | 4.4          | 1.9            | 0.15        | Shigeyama et al. 1990 |
| 1994I  | Ic   | 1.0    | 0.9          | ...            | 0.07        | Nomoto et al. 2000 |
| 2002ap | Ic   | 7.0    | 3.75         | ...            | 0.07        | Mazzali et al. 2002 |
| 1997ef | Ic   | 8.0    | 7.6          | ...            | 0.15        | Nomoto et al. 2000 |
| 1998bw | Ic   | 60.0   | 10.0         | ...            | 0.50        | Nomoto et al. 2000 |

Nomoto and collaborators have modeled SNe Ib as helium stars that lose
their hydrogen envelopes prior to explosion by mass transfer to a binary com-
panion, and SNe Ic as C/O bare cores that lose their helium envelopes in a
second stage of mass transfer. In all cases they assume that these SNe are
spherically symmetric. Given the high levels of polarization displayed by some
of these objects (e.g. Wang et al. 2001, Leonard et al. 2002c), this might not
be an accurate approximation. Keeping in mind this caveat we list in Table 3
their results and the physical parameters they derive for the three hypernovae
and four normal Type Ib and Ic events.

Fig. 15 shows how the ejected masses and 56Ni yields vary with explosion
energy for the seven Type Ib and Type Ic SNe (crosses) listed in Table 3, along
with the 16 classical SNe II (filled circles) shown in Fig. 7. The top panel
reveals that SNe Ib and SNe Ic appear to follow the same pattern shown by
classical SNe II, namely, that more energetic SNe eject greater masses. The
main difference between both subtypes, of course, is the vertical offset caused
by the strong mass loss suffered by SNe Ib and SNe Ic prior to explosion. This
suggests that the mass of the envelope is one of the driving parameters of the
explosion for CCSNe, or that it is correlated with some other property of the
core, with the latter determining the outcome of the collapse.

These plots permit one to appreciate that the distinguishing characteristic of
the three hypernovae is the great explosion energy, between 7 and 60 foes, far
above the normal Ib and Ic events which are characterized by energies 1 foe
(note, however, that this conclusion is based on spherically symmetric models;
Höflich et al. (1999) showed that the energy of SN 1998bw could be as low as
2 foes when an ellipsoidal geometry for the ejecta is assumed). When
the whole sample of CCSNe is considered there is a continous distribution of
energies below 8 foes. Within this regime it appears that some Type II events such as SN 1992am reach explosion energies comparable to that of the hypernovae SN 1997ef and SN 2002ap. *This demonstrates that, in terms of energy, the definition of hypernova is not clear cut.* Whether the energy distribution is continuous above 8 foes remains to be seen when more data become available. This will permit us to understand if SN 1998bw belongs to a separate class of object or if it just lies at the extreme of the family of CCSNe. At the moment it is fair to say that there is only one firm SN/GRB association and, within the SN context, this object was clearly exceptional regarding its explosion energy.

The bottom panel reveals that SN 1998bw was not only remarkable in explosion energy (60 foes), but also in a high nickel yield (0.5 \( M_\odot \)). Despite their greater than normal energies, none of the other two Type Ic hypernovae (SN 1997ef and SN 2002ap) produced unusually higher nickel masses compared to the other CCSNe. In fact the Type II SN 1992am ejected even more \(^{56}\text{Ni}\) (0.26 \( M_\odot \)) than these two hypernovae. This suggests that there is continuum in \(^{56}\text{Ni}\) yields below 0.3 \( M_\odot \) for all CCSNe. More data are needed to ascertain whether this continuity extends up to SN 1998bw.

Leaving aside SN 1998bw, it proves interesting that all other CCSNe share the same location in the \(^{56}\text{Ni}/\text{energy}\) plane. Since both of these parameters...
carry imprints from the physical conditions very close to the center of the explosion, this suggests that the physics of the core and explosion mechanisms of all CCSNe are not be fundamentally different.

3. Summary and Discussion

The general properties of the different CCSNe mentioned above are summarized in Table 4.

Table 4. General Properties of Core Collapse Supernovae.

| Spectroscopic Type | Relative Frequency (Observed) | Photometric Type | Mass Loss Rate \(10^6 \text{M}_\odot \text{yr}^{-1}\) | Ejected Mass \(\text{M}_\odot\) |
|-------------------|-------------------------------|-----------------|-----------------------------------|---------------------|
| II                | 45%                           | plateau,87A-like| low                               | 14-56               |
| II,II, Ic        | 30%                           | linear,slow     | 10-700                            | < 6                 |
| Ib+Ic            | 25%                           | bell-like       | 1-26                              | 1-10                |

* Based on the LOTOSS (Li et al. 2000) discoveries reported to the IAU Circulars in 2001. No attempt has been made here to correct the observed frequencies from selection biases. The intrinsic SN rates must await the analysis of the observation history of the LOTOSS galaxy sample.

There are clear examples of intermediate spectroscopic cases in the CCSN family. With intermediate He I line strengths, SN 1999ex provides a clear link between the Ib and Ic classes (Hamuy et al. 2002). The metamorphosis of SN 1993J from a Type II SN into a Ib event (Filippenko et al. 1993) provides evidence for an intermediate IIb case. This is strong evidence for a continuous spectroscopic sequence (II-IIb-Ib-Ib/c-Ic) among CCSNe, which reflects the ability of the SN progenitors to retain their H-rich and He-rich envelopes prior to explosion. Another factor that defines the appearance of a SN is the density of the medium in which they explode, which is determined by the history of mass-loss of the SN progenitor.

There is a wide range in explosion energies (0.6-60 foes), ejected masses, and \(^{56}\text{Ni}\) yields (0.0016-0.5 \(\text{M}_\odot\)) among CCSNe, even within the same spectroscopic type. Classical SNe II show a trend in the sense that SNe with greater envelope masses produce more energetic explosions (Fig. 15). Type Ib and Ic appear to follow the same pattern. This suggests that the mass of the envelope is one of the driving parameters of the explosion, or that it is correlated with some other property of the core, with the latter determining the outcome of the collapse.

Type II, Ib, and Ic SNe share the same location in the \(^{56}\text{Ni}/\text{energy}\) plane. Since both of these parameters carry imprints from the physical conditions very close to the center of the explosion, this suggests that the physics of the core
and explosion mechanisms of all CCSNe are not be fundamentally different, regardless of the external appearance of these objects.

At the moment it is fair to say that there is only one firm SN/GRB association (SN 1998bw), and this object was clearly exceptional regarding energy and nickel production within the SN context.

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