Chapter 1

SUPERNOVAE AS ASTROPHYSICAL OBJECTS

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Abstract Supernovae are a prominent component of modern astrophysics. They are responsible for a major part of the chemical enrichment in the universe and the main recycling mechanism in galaxies. The physics of these explosions is fairly well, although not completely, understood.

This article reviews the current understanding of the supernova explosions. After a brief historical introduction the two main classes of supernovae are described starting from the classification scheme currently employed. The different energy inputs for supernovae are presented. Despite their rather different energy sources supernovae from different types reach very similar luminosities. A notable exception to this are the Gamma-Ray Bursts, which are several orders of magnitude more energetic. The characteristics of each supernova type are presented.

Keywords: Supernovae; explosion physics; chemical enrichment

1. Some History

Stellar explosions are among the most violent events in the universe. The appearance of new stars, "stellae novae" from their Latin designation, has always intrigued astronomers as documented in the ancient Chinese and Korean records (see Clark & Stephenson 1977 [9] and Murdin & Murdin 1978 [46] for reviews of the historic supernovae). The 'stella nova' in Cassiopeia, which appeared in November 1572, was observed by the young Tycho Brahe. It strongly impressed him and led him to conclude that the object, due to lack of an observable parallax, had to be outside the solar system and could not be explained in the

Ptolemaic system of crystal spheres [4]. Some 150 years later Lundmark [36] suggested that there are two classes of novae, an 'upper class' which would be about 10 magnitudes brighter than a 'lower class' of novae. The latter would correspond to the well known Galactic novae. He based his proposal mostly on the observation of the nova 'S Andromeda' observed in 1885 (designated SN 1885A in modern nomenclature), which appeared that much brighter than a sample of about two dozen regular novae in the Andromeda galaxy. Lundmark later seemingly was the first to suggest the name 'super-nova' [37]. Walter Baade and Fritz Zwicky [3] as well realised that stellar explosions come in different flavours.

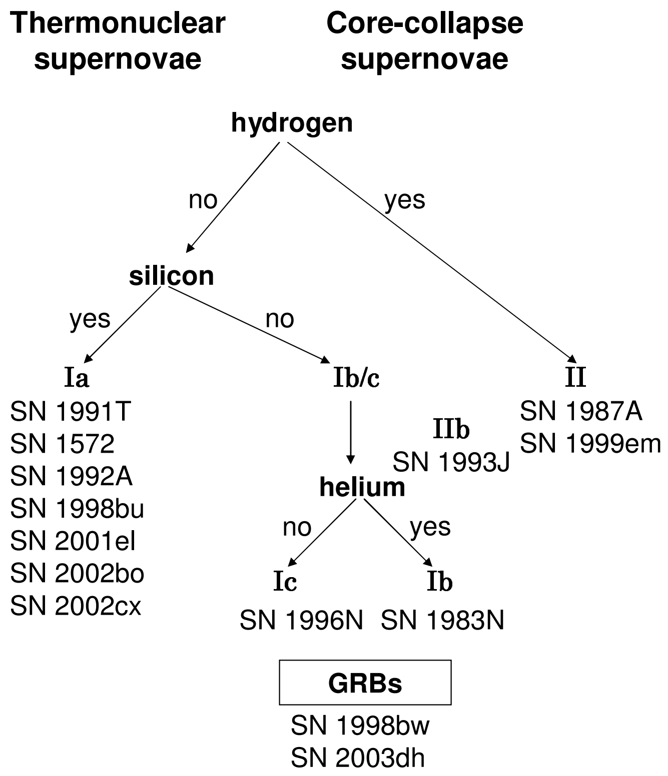
It was Walter Baade who made the connection between the historical supernovae and the observed emission nebulae at their positions, thus identifying the remnants of the explosions. The most prominent object is of course the Crab Nebular (Messier 1), the leftover from the supernova in 1054 [2, 39]. With extensive observations of bright supernovae Minkowski [45] introduced two subclasses. Zwicky [60] refined the classification scheme for supernovae further. However, for several decades only two main classes were maintained until in the early eighties it became clear that at least one further subclass needs to be added.

The understanding of supernova physics is moving rapidly and at any given time only a snapshot is possible. The most recent reviews can be found in Hillebrandt & Leibundgut [24] and Weiler [59]. More specific reviews on Type Ia supernovae are Leibundgut [28] and Meikle [44]. The Type II supernovae have been discussed in Arnett et al. [1] and McCray [42] in connection with SN 1987A.

2. Supernova classification

The modern classification of supernovae is based on the spectroscopy around maximum light (e.g. [16, 57] - see also Fig. 1.1). The distinction is done through the presence (or absence) of hydrogen lines leading to the classes of Type II supernovae (or Type I supernovae). The hydrogen-deficient supernovae are further subdivided into groups which display prominent absorption near 6150Å attributed to Si II for the Type Ia supernovae and others which show Na and oxygen lines, called Type Ib/c supernovae. The presence/absence of helium lines is often argued for a separation into the Type Ib/Type Ic supernovae, respectively. One should note that these classifications are based on optical spectroscopy. The IR He I (λ10830Å) line has been observed in many Type Ic supernovae by now. Moreover, there is one 'cross-over' class of Type IIb supernovae. These typically start out as hydrogen bearing supernovae before the hydrogen lines disappear and the objects start to

Figure 1.1. Classification scheme for supernovae



resemble Type Ib/c supernovae. They are the major link showing that the SNe Ib/c are core-collapse objects. Figure 1.1 also lists some typical example for each SN class.

Most importantly, a physical picture for this classification scheme has emerged. The Type Ia supernovae (SNe Ia hereafter) are coming from thermonuclear explosions of objects, which have shed hydrogen and helium during their progenitor evolution. Hence no traces from these elements are observed in these explosions. All other supernovae most likely come from core-collapse explosions. The signature for these objects are their oxygen and calcium rich spectra at late phases. The general characteristics of the supernova types are shown in Table 1.1.

The entries in Table 1.1 can be traced back to observational results. The mass and size of the progenitor stars can be evaluated best from

Table 1.1. Characteristics of supernova types

Thermonuclear Supernovae	**Core-collapse Supernovae**
from low-mass stars ($M < 8M_\odot$)	high-mass stars ($M > 8M_\odot$)
highly evolved stars (white dwarfs)	large envelopes (core still burning)
explosive carbon and oxygen burning	burning due to compression of the infalling material
binary system required	single stars (binaries for SNe Ib/c)
complete disruption	neutron star (or black hole) remnant

the bolometric light curves, i.e. the integrated energy radiated in the electromagnetic spectrum (e.g. [30, 1]. The presence of only higher elements in SNe Ia is an indication that they come from stars that have shed their envelopes a long time ago. The core-collapse in massive stars is triggered by the fact that only endo-thermal nuclear fusion is possible beyond the iron peak, the most tightly bound nuclei, and the pressure in the centre of the star is removed triggering the collapse. The burning mechanisms in the two types is entirely different. While SNe Ia are incinerated from the inside out, with a flame moving through the star, burning oxygen and carbon explosively up to the iron-peak elements, the core-collapse produces high-density and high-temperature zones near the surface of the forming neutron star where material is compressed and nuclear burning is initiated. Since the explosion in SNe Ia are suspected to come from white dwarfs, which are normally simply cooling by radiating away the energy they gain from the gravitational shrinking of the star, they need to be triggered into an explosion. The natural point is the situation where the electron pressure can no longer support the white dwarf, which happens when it reaches the Chandrasekhar mass [7]. Hence most models predict a companion star losing mass that is accreted by the white dwarf to grow to the Chandrasekhar mass. It should be noted that currently no consensus has been reached on what the companion star is (e.g. [5, 35]. For SNe II there is no need to invoke a companion star for the explosion. However, for the subtype of the SNe Ib/c where the hydrogen layer has been lost, a companion is often suggested as the mechanism to remove the hydrogen envelope. Contrary to the SNe Ia here the companion is not a donor, but used to expel the envelope. And finally, core-collapse supernovae do leave a compact remnant, either a neutron star or a black hole, while the thermonuclear explosions burn and disrupt the star entirely.

3. Input Energy

It is interesting to evaluate the energy sources of the two explosion mechanisms. Gravity is the drive behind the core-collapse supernovae. The collapse of about 1.5 $M_\odot$ to nuclear densities or beyond release about 10^{53} erg. Most of this energy is radiated in anti-neutrinos, which escape in the formation of neutrons out of protons and electrons. About 10^{51} erg go into kinetic energy pushing the envelope away and only 10^{49} erg go into electromagnetic radiation signalling the death of the star across the universe. The thermonuclear explosions draw their energy from the energy difference of the binding energy of oxygen and carbon compared to the iron-peak elements. About one solar mass of O and C are burned and an energy of 10^{49} erg is released in electro-magnetic radiation.

There are several effects that can influence the electro-magnetic display of supernovae. Shocks further convert kinetic energy into radiation. Some of the radiation can not escape the dense explosion and only when the debris expand and adiabatically cool is some of it released. Energy that went into ionising the envelope is released when the material cools down enough so that the atoms recombine again. For supernovae with extended envelope this recombination can create an extended plateau phase in the light curve, where the expansion of the atmosphere is balanced by the inward moving wave of recombination. One of the best observed examples is SN 1999em [20, 12] where the plateau lasted for about 100 days.

However, the largest energy reservoir is stored in radioactive isotopes that release $\gamma-$rays after typical decay times. The most important channel is the $\gamma-$decay of ^{56}Ni into ^{56}Co and then stable ^{56}Fe (e.g. [11]. For the core-collapse supernovae this channel provides the energy input for the late light curves (after the plateau phase), while it is the only energy input for SNe Ia [31]. Bolometric light curves can be used to track the change in escape fraction of the $\gamma-$rays from the supernova ejecta [30, 10].

For massive supernovae the absolute luminosity after about 120 days, together with the age of the supernova, gives a relatively accurate measure of the amount of ^{56}Co synthesised in the explosion [22, 12]. This measurement is now available for many core-collapse supernovae and is typically a factor 10 less than assumed in thermonuclear supernovae but spans almost a factor of 100 [47].

The long and rich light curve observed for SN 1987A is a clear demonstration of how the various physical effects form the light curve [31]. It shows many of the described features and some more.

Hypernovae have been added to the list of supernovae and they represent the high energy end (at least in their kinematics) with the high velocities observed in these objects. The connection of gamma–ray burst with supernovae has now been generally accepted with the observations of SN 2003dh/GRB030329 (e.g. [54, 38, 26]. It should be noted that already SN 1998bw/GRB980425 showed all the signatures of a supernova [18, 48]. These hypernovae are characterised by the absence of hydrogen and helium and very high expansion velocities observed in the spectra [40, 41]. In some cases no gamma-ray burst is observed, like for SN 2002ap. The amount of nickel synthesised in these explosions is substantial, up to about 0.5 $M_{\odot}$ [53]. The kinetic energies inferred from the line widths are also substantially larger than the ones of regular SNe II. In many aspects they appear to be similar to the SNe Ib/c with high kinetic energy.

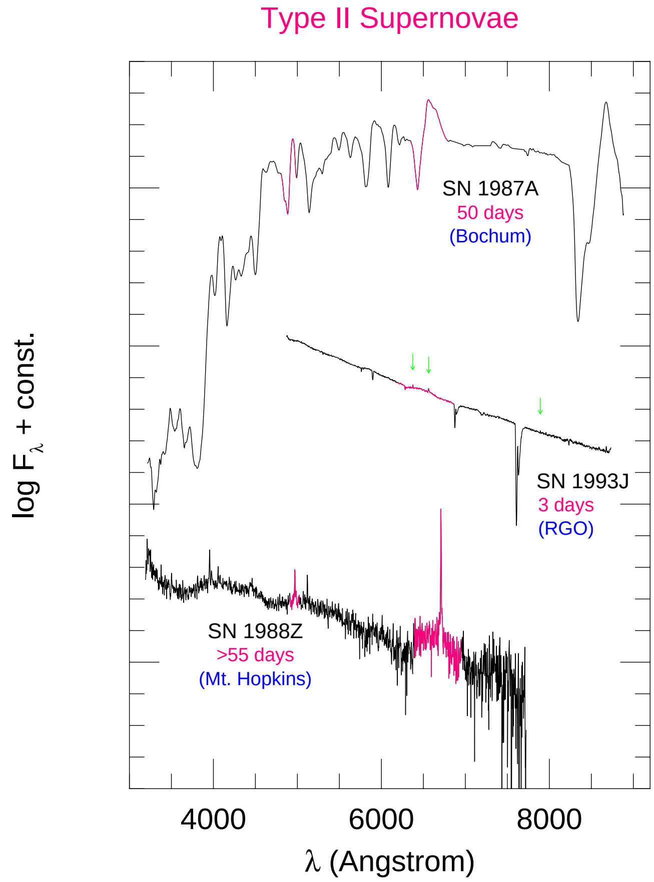
4. Core-collapse supernovae

The richness in appearance of the core-collapse supernovae is due to their varied progenitor histories. An example of the appearance of SNe II is given in Figure 1.2. The spectra have all been observed near maximum light and show Hα in these objects. The typical light curves of SNe II displays a long plateau of about 100 days after the maximum. The most prominent and best observed case after SN 1987A is SN 1999em [20, 12]. While SN 1987A displays a strong P Cygni line, it is almost not visible in SN 1993J. The latter lost this line in its evolution completely and only after about one year did Hα reemerge in the nebular spectrum [15]. The case of SN 1988Z is different again. In this case, the hydrogen is excited in circumstellar material shocked by the supernova shock. The time of explosion for this object is not known very well [55] and it is likely that it exploded several months before it was discovered. The emission is dominated by the shock energy and not recombination or radioactive decay as in all other supernovae.

This special case of supernovae interacting early on with their dense circumstellar environment is discussed in Chevalier & Fransson [8] and Leibundgut [27]. They typically have very slow light curves and spectra that show emission lines but very little absorption. The best studied cases so far are SN 1986J [29], SN 1988Z [56], SN 1995N [17] and SN 1998S [13]. These objects often can be observed for many years and show very little evolution.

Most Gamma-Ray Bursts are now also classified as supernovae. Their connection became clear with the observations of SN 1998bw/GRB980425 [18, 48] and more recently with SN 2003dh/GRB030329 [26, 38]. Other

Figure 1.2. Examples of Type II supernova spectra. The references for the spectra are SN 1987A: Hanuschik & Dachs 1988; SN 1993J: Lewis et al. 1994; SN 1988Z: Filippenko 1991.



examples include SN 2002ap [40] and SN 1999cy [19, 58]. These objects probably have a core that collapses to a black hole and produce relativistic jets. The interaction of these jets with the stellar atmosphere and surrounding material produce the $\gamma-$ray flashes and the optical afterglows [43].

5. Type Ia supernovae

Although thermonuclear supernovae have simpler underlying physics than the core-collapse supernovae, there still remain formidable hurdles to fully understand them [25]. The observational material that has been assembled in the last decade is considerable and many nearby supernovae are now observed with exquisite detail. The last four years have seen dramatic progress in recognising peculiar events and also determining specific characteristics. The situation a few years ago is described in Leibundgut [28]. Since then the peculiar SN 2000cx [33, 6] and SN 2002cx [34] have been observed. A truly particular case has been discovered in SN 2001ic [21], which displayed a strong, broad-lined Hα emission after about 90 days past the maximum. This supernovae early on had all the signatures of a bright SN Ia with what looked like residual Hα emission from the host galaxy. The spectral sequence later showed that the hydrogen emission is intrinsic to the supernova and indicates that this explosion occurred inside a dense hydrogen cocoon. These objects have thrown a dark shadow over the light curve – luminosity relations that have been used in the past to normalise the peak luminosity [50, 52, 49] and derive cosmological distances. They highlight the fact that not all SNe Ia are identical. The differences provide us with a tool to further investigate the true nature of these explosions. Of most import are currently the distribution of the synthesised nickel mass in the explosion, the mass of the progenitor star - and hence the ejecta - and the explosion energy. These affect the light curves in very specific ways [51].

The ability to determine a normalised peak luminosity for these objects has allowed us to measure accurate cosmological distances. The implications of this capability and the inferred cosmological results will be described in the following paper.

6. Conclusions

The term supernovae describes very different explosive processes in astronomy. There are essentially two object classes that provide an observable display that is rather similar. One is the core-collapse in a massive star where the freed gravitational energy is turned into radiation in many different ways. The rich variety of core-collapse supernovae is due to the many evolutionary channels that lead to such explosions. In addition, core-collapse in massive stars occurs in rather dense astronomical environments – near or in star forming regions – and in stars at different evolutionary phases at the outside.

The thermonuclear explosions are much closer to what has been termed a 'standard bomb' as they presumably are coming from a highly evolved stellar state, white dwarfs, that represent an old population.

The physics of the explosions are not completely understood in both cases. For the core-collapse supernovae there are also many effects which influence the appearance of the supernovae [31]. The variations are a possible way to improve our understanding of these objects.

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