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CICLO XVIII

AUTOMATIC OBJECTIVE CLASSIFICATION OF SUPERNOVAE

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Abstract

In this Thesis I present the tools for an automatic, objective classification of Supernova (SN) spectra I have developed within the Padova SN group, as well as several scientific applications of these tools.

The classification of SNe is one of the fundamental issues of our study. The final aim of the classification is the ordering vast arrays of SNe in groups on the basis of their intrinsic physical properties. Our capacity to classify SNe is limited by our understanding of their physics, hence, the current classification scheme is still confused and unsatisfactory. Among many classes and subclasses only the most experienced specialists are able to orientate themselves. Thus, the classifications of not obvious events might often be subjective or biased.

In a situation like this a way out and also a conservative approach to SN classification is the comparison of SN spectra with those of other well studied SNe. Such a comparison, performed in an automatic and quantitative manner, is able to sort out the objects with similar properties (i.e. to classify them) in an objective way.

Therefore, the first, necessary ingredient for an objective classification is an archive of SN spectra, i.e. a large number of SN spectra of different types, to be used as templates spanning a wide range of properties. In our case, the templates come from Asiago SN spectra archive which is presented in Chapter 2, along with the current amount of data, the SNe included in it and their main properties (types, redshifts, phases). The archive contains SNe of all types (including peculiar ones) with various properties and having an extended temporal coverage. We stress that this is an essential issue, since number and variety of SN spectra in the archive have a direct impact on the ability of the comparison software to identify a given SN. The large number of spectra and the continuous additions to the archive required automatic procedures for the data management. I spent the first months of my PhD developing the software for organisation, update and enrichment of the archive data.

The core ingredient of the objective classification is the software for SN spectra comparison. Chapter 3 presents the PAdova SN Spectra comPARison TOOl (PASSPARTOO), a collection of procedures developed by the author to this aim. Among these programs, the Generic cLAssification TOol (GELATO) is the most used. The algorithm, optimised for classification of SNe, is described in detail. In particular, the creation of the templates with an almost lossless technique of SN spectra processing is presented. Further, the methods for finding the best match template and for a quantitative evaluation of "goodness-of-fits" are described. Not only I show the GELATO's ability to classify SNe, but also its potential to estimate the ages of SN spectra, i.e. the time elapsed from the maximum light (or epoch of the explo-

sion). The chapter is concluded by an overview of the other spectra comparison procedures available, by a critical discussion on the novelty of our approach and by the perspective of future improvements. Currently GELATO is routinely used by the members of Padova SN group for classification and ageing of newly discovered objects, as well as for comparative studies of SN spectra.

In Chapter 4 I then show how the application of the above mentioned components into a single complete classification tool has been applied to our SN studies. I describe, in particular (Section 4.1), how our tools were used for an analysis of SN spectra obtained by the European Supernova Collaboration, never studied in detail and published before. The observational data, obtained by 7 different telescope-instruments combinations, were reduced and analysed. The important information from the spectra, like the expansion velocities, reddening and possible peculiarities of the corresponding SNe were extracted. Finally, using GELATO we verified the original classification of the objects and estimated their ages. GELATO showed to be a valuable tool for this kind of "a posteriori" analysis. The results of this study are being published in A&A (Harutyunyan et al., 2008, submitted).

In the following section of the chapter (Section 4.2) I present the on-going SN classification program at Telescopio Nazionale Galileo (TNG) leaded by me. The program, initially approved for two periods, was aimed to the early-time observations of SNe and to select targets for further observational campaigns. The Target of Opportunity (ToO) observations of newly discovered SNe were followed by the rapid and efficient reduction of the data and, then, the reduced spectra were classified using GELATO. This latter showed to be a fast and reliable instrument in such "real-time" application. The program gave more than ten SN classification, which were published in the telegrams of IAU Central Bureau of Astronomical Telegrams (CBAT). The same analysis of newly discovered SNe is now an integral part of the long-term project on SNe at TNG. The most important achievement of the program were the prompt classifications of two extraordinary objects, SNe 2006gy and 2006jc, which were correctly classified as peculiar SNe, while other groups failed. The further observations and detailed studies of the data obtained suggested new new classes of SN progenitors and novel explosion mechanisms. Not only our classification program was crucial for the identification of these objects, but also the early-time spectra of these SNe obtained during the program were very important inputs for their study. Section 4.2 provides a more detailed discussion on these objects, highlighting the most important results obtained.

Section 4.3 is devoted to SN 2002ic, an object whose nature has been largely debated. The observational properties of the object were interpreted by an explosion of a type-Ia SN with a dense H-rich circum-stellar matter (CSM) around it. Our work, based on a PASSPARTOO analysis, suggested a new classification as type Ic. During the study, the objective classification of SN 2002ic showing its similarity to the type-Ic SNe was one of the important clues, which suggested the true nature of this explosion.

Chapter 5 summarises the Thesis and discusses the important issues for the future work.

Riassunto

In questa Tesi presento il progetto, sviluppato nell'ambito del gruppo di Supernovae (SNe) di Padova, per una classificazione automatica ed oggettiva delle Supernovae. Sono inoltre discusse un numero di applicazioni scientifiche del package sviluppato che sono state pubblcate su riviste specializzate.

La classificazione delle SNe è uno prerequisito fondamentale del loro studio. L'obiettivo finale della classificazione è il raggruppamento delle varie SNe in gruppi omogenei sulla base di proprietà fisiche intrinseche. La nostra limitata conoscenza della fisica delle SNe si riflette nella incapacità di classificare le SNe. Di conseguenza l'attuale schema di classificazione è confuso e insoddisfacente. Solo gli specialisti più esperti riescono ad orientarsi tra le tante classi e sottoclassi introdotte finora e la classificazione di eventi non comuni può spesso essere soggettiva e contrversa.

In una situazione come questa, il raggruppamento delle SNe tramite il confronto con un campione di SNe ben studiate (templates) è un approccio forse poco elegante ma certamente efficace. Un siffatto confronto, eseguito in maniera automatica, è in grado di raggruppare in modo quantitativo ed impersonale gli oggetti con proprietà simili, cioè di classificarli.

Il primo, essenziale componente necessario per una classificazione oggettiva tramite confronto è la disponibilitá di un ricco archivio di spettri di SNe che fornisca i templates di confronto, i.e. i numerosi spettri di SNe dei diversi tipi, che coprono la piú ampia varietà di comportamenti. Nel nostro caso gli spettri di confronto sono forniti dall'Archivio di SNe di Asiago (ASA). Nel Capitolo 2 presento questo archivio, la sua struttura, estensione e le principali proprietà delle SNe che lo compongono (tipi spettrali, redshift, fase, ecc.). L'archivio, infatti, contiene spettri di tutte le molteplici classi di SNe (incluse quelle peculiari) e per ciascuna classe la copertura temporale è piuttosto buona. Come verrá sottolineati piú volte, questo è un punto importante perché la completezza dell'archivio ha un impatto diretto sulla capacità del software di confronto di classificare le nuove SNe. Per la grande quantità di spettri contenuti e, soprattutto, per la necessitá di un continuo aggiornamento dell'archivio con nuovi dati si è reso necessario lo sviluppo di una serie di procedure automatiche per la gestione dell'archivio. Tali procedure da me sviluppate, essendo parte integrante del presente lavoro verranno ampiamente discusse nella tesi.

L'altro indispensabile ingrediente per una ottimale classificazione oggettiva è naturalmente il software di confronto degli spettri di SNe PASSPARTOO (PAdova Sn Spectra comPARison TOOl), da me sviluppato e che verrà descritto nel corso del Capitolo 3. In realtà PASSPARTOO è un insieme di più procedure di cui GEneric cLAssification TOol (GELATO) è la più usata per il confronto degli spettri.

L'algoritmo, ottimizzato per la classificazione di SNe, verrà descitto in maniera dettagliata con particolare riferimento alla creazione dei templates per mezzo di una tecnica conservativa di elaborazione degli spettri. Inoltre verranno descritti sia l'algoritmo con cui viene trovato lo spettro d'archivio più somigliante, che l'algoritmo che valuta quantitativamente la bontà del fit. Infine vengono descritte non solo le performances di GELATO di classificare le SNe, ma anche il suo potenziale nello stimare le età degli spettri di SNe. Nell'ultima parte del capitolo si presentano altri SW di confronto spettrale sviluppati da altri gruppi attivi nel campo delle SNe. Il confronto di GELATO con questi software di letteratura mette in evidenza il nostro approccio innovativo sviluppato per il confronto di spettri, evidenziandone già i futuri miglioramenti. Attualmente GELATO è sistematicamente usato dai ricercatori del gruppo di SNe di Padova sia per la classificazione di nuovi oggetti scoperti, sia nello studio comparativo e sistematico di differenti SNe.

Nel Capitolo 4 descrivo come la combinazione di archivio piú SW sia stata effettivamente applicata allo studio delle SNe. In particolare, descrivo (paragrafo 4.1) come essi siano stati usati per l'analisi degli spettri di SNe ottenuti dall'European Supernova Collaboration che non erano ancora stati nè studiati nè publicati. Inizialmente le tutte osservazioni, ottenute con l'ausilio di 7 differenti combinazioni di telescopi / strumenti, sono state raccolte, ridotte e successivamente analizzate. Abbiamo così potuto estrarre dagli spettri ridotti importanti informazioni fisiche sulle esplosioni medesime, come le velocità di espansione degli ejecta, l'arrossamento subito dalla luce nell'attraversare nubi di polvere circum-interstellare ed eventuali proprietà peculiari delle SNe. Naturalmente, usando GELATO abbiamo verificato le classificazioni originali degli oggetti e abbiamo stimato con migliore precisione le loro età al momento della scoperta. GELATO si è dimostrato un prezioso strumento anche per questo tipo di analisi "a posteriori". I risultati di questo mio studio sono in pubblicazione in A&A.

Nel paragrafo 4.2 presento il mio progetto di classificazione di SNe con il Telescopio Nazionale Galileo. Il programma che ha ricevuto tempo osservativo in due periodi consecutivi (AOT15 e AOT16) e che in AOT17 è confluito in un piú vasto "large program", aveva come scopo la rapidissima classificazione spettroscopica di SNe relativamente vicine, allo scopo di selezionare target interessanti per successive, estese campagne osservative. Le osservazioni sono state eseguite in modalità Target of Oppotunity (ToO), i dati venivano trasferiti quasi in tempo reale a Padova ed immediatamente ridotti. Gli spettri così ottenuti venivano immediatamente classificati usando GELATO, che si è dimostrato essere veloce ed affidabile anche in queste applicazioni "real-time". Con questo programma osservativo abbiamo classificato più di una decina di SNe e le rispettive comunicazioni sono state pubblicate nelle CBAT dell'IAU Central Bureau of Astronomical Telegrams. Il risultato più importante di tale programma osservativo è stata la classificazione di due oggetti straordinari: SNe 2006gy e 2006jc. Le successive osservazioni e il loro studio dettagliato hanno dimostrato la natura peculiarissima di queste due SNe, che hanno richiesto l'introduzione di nuovi classi di progenitori e nuovi meccanismi di esplosione. Il nostro programma di rapida classificazione è stato cruciale non solo per l'identificazione di questi oggetti, ma anche per ottenere i primissimi ed unici spettri che si sono rivelati fondamentali nello studio di queste SNe dando preziose informazioni sugli strati più esterni dell'inviluppo in espansione.

Il paragrafo 4.3 è dedicato ad un'altra straordinaria esplosione, SN 2002ic, la vera natura della quale è stata oggetto di un vivace dibattito in letteratura. Le proprietà osservate sono stati interpretate con l'interazione tra gli ejecta di una esplosione termonucleare di una nana bianca (cioè una supernova di tipo Ia) con del materiale circum-stellare ricco di H perso dalla sua compagna. In alternativa il nostro lavoro (Benetti et al. 2006b) ha suggerito invece uno scenario diverso, ossia il collasso di un core di una stella massiccia (quindi una supernova di tipo Ic), configurazione più congruente con le evidenze di un denso materiale circumstellare attorno al progenitore. In questo studio, la classificazione oggettiva di SN 2002ic, attraverso PASSPARTOO è stata determinante per scoprire la vera natura di questa esplosione.

La tesi si conclude con un rapido riepilogo dei risultati raggiunti nel presente lavoro e le prospettive per i lavori futuri (Capitolo 5).

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Introduction to Supernovae and Motivation

A SUPERNOVA IS AN EXPLOSION occurring at the end of a star's life that destroys the star (either completely, or leaving only a compact nucleus). During the explosion an enormous amount of energy ($\sim 10^{51}$ erg) is released, and the interstellar medium is enriched by heavy elements synthesized by the star through its evolution and explosion. Not only Supernovae (SNe) play important role in stellar evolution and creation of heavy elements, but are also powerful cosmological tools as well as responsible for gamma-ray bursts. Thus, the study of SNe is crucial in our understanding the structure, age and evolution of the Universe.

1.1 Supernova discoveries

Although only a small fraction of a SN explosion energy is released in the form of visible light, the exploding star becomes as bright as the whole galaxy in which it is embedded. In the historical past SNe exploded in our galaxy were visible by naked eye in broad daylight and were believed by our ancestors to be new stars born in the sky, thus, called "novae" ("new stars" in latin).

New stars were recorded by ancient european and asian chronicles. While we know that in many cases these new stars were comets, the others were what we now call novae and supernovae. Using constraints on the duration of the temporary stars, the brilliance and number of independent records, seven or eight supernovae have been confirmed from historical chronicles by Stephenson & Green (2005).

By the early '20s few bright SNe have been discovered, including that of the 1885 in the Andromeda galaxy, and at some point it was realised that there was a distinct class of bright novae (Lundmark 1925). After Hubble's works, when the extragalactic nebulae were placed at their actual distances, it was understood that the novae occurring in these nebulae were more distant and thus established their very high luminosity. Baade & Zwicky (1934) defined these events as "supernovae". Few years later the first systematic SN search (1936-1941) was started by Baade and Zwicky using the Palomar 18-inch Schmidt telescope and led to discovery of 19 SNe. During the same period the SNe started to be catalogued, identified by the discovery year followed by a letter of the alphabet indicating the chronological order of discovery.

In those years first well-sampled data on SNe started to appear and lead Minkowski to a provisional division of SNe into two groups: type I and type II. The groups were distinguished on the basis of absence or presence of hydrogen lines in their early spectra (Minkowski 1941). After more than half a century this “provisional” classification is still in use, though with some more subdivisions and specifications.

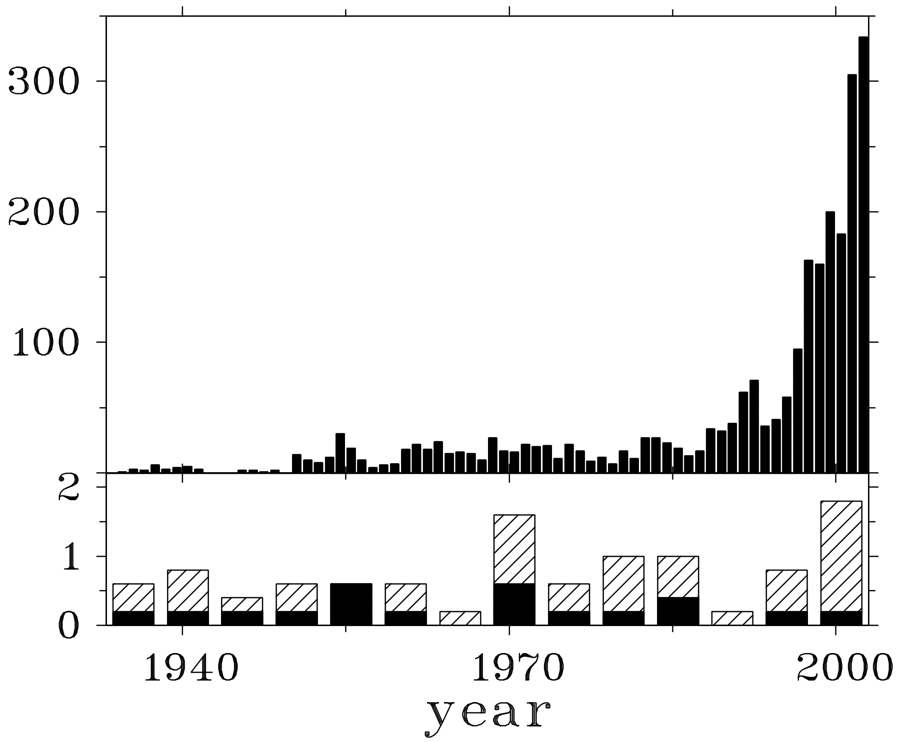


FIGURE 1.1– Number of SN discoveries per year (top panel). Number of SNe within a distance of 10 Mpc (shaded area) or 5 Mpc (filled area), averaged over 5 years (bottom panel). From Cappellaro (2005).

In the following years (after the barren period due to the world war), SN searches were continued using new Schmidt telescopes and the worldwide interest towards the SNe grew. In the beginning of the ’80s the contribution of southern SN searches became important. Thanks to this huge observational effort and long-term commitment it has been possible to have a statistically sufficient number of SN discoveries. Using the data of SN searches by that period, it was possible to derive the accurate estimates of the SN rates in the different types of galaxies (Cappellaro & Turatto 1988; Cappellaro et al. 1999), which in the epoch of automatic SN searches are still widely used as reference values.

The discovery of 1987A, the brightest SN in almost four centuries, returned SNe as one of the hottest topics of astronomical research, causing an explosion of the number of consequent SN discoveries (see Figure 1.1). Currently, in the epoch of automatic SN discoveries, more than 300 SNe are discovered every year. However, the contribution of the enthusiastic amateurs should not be underestimated. Indeed, over 50% of the very nearby SNe (v_{hel}) < 1000 km s^{-1}) of the last ten years have been discovered by amateurs (Cappellaro 2005).

According to the Asiago Supernova Catalogue (see Section 2.4) more than 4200 SNe were discovered by the October 2007. Despite the rather large number of the SNe discovered so far, only a fraction of those SNe are nearby, hence, in principle available for detailed studies (only 1020 SNe with redshift z $\leq$ 0.01). The real number of well studied SNe is probably a few hundreds, showing that our studies of SNe are still limited.

The many ongoing or planned SN searches for nearby and distant SNe testify that the interest for SNe is still on the raise and it is easy to predict that the number of SN discoveries will continue to grow in the next years.

1.2 Types of Supernovae

As mentioned in the previous section, in 1941 Minkowski divided SNe into two types, depending on the absence (type I) or presence (type II) of hydrogen lines in the spectra. Since then some new SN types were introduced, others dismissed and in the ’80s a classification scheme started to take shape. On the basis of optical spectra near maximum light the SNe were divided in four main classes (see Figure 1.2; from Turatto 2003):

- SNe Ia: the spectra show Si II lines but no H I. This class corresponds to the Type I SNe by Minkowski;
- SNe Ib: with spectra dominated by He I lines. The spectra do not have Si II lines, neither H I;
- SNe Ic: the spectra lack both Si II and H I lines. The He I lines are absent of very weak;
- SNe II: the spectra are dominated by H I lines at all epochs (corresponds to the Type II SNe group by Minkowski).

Later on the photometric information like the behaviour of the light curves and the spectra at later epochs of the evolution were used to refine the classification. This led, for instance, to the introduction of several subclasses of type-II SNe, based on the appearances of the light curves (see Figure 1.3; from Wheeler & Benetti 2000) and in some cases also spectral evolution.

- SNe IIP: with light curves that after maximum show a period of almost constant luminosity, the plateau, lasting from a few weeks to more than 100 days.
- SNe IIL: with a linear uninterrupted decline of luminosity after maximum.
- SNe IIb: photometrically similar to SNe Ib/c but with spectra that show strong H I lines during the first weeks after explosion. Later on the spectra start to show He I lines similarly to SNe Ib. These are therefore a link between the two classes, supporting the idea that SNe II and SNe Ib/c come from the same kind of progenitors and explosion mechanism.
- SNe IIn: with slowly declining light curves and spectra showing blue continua and multicomponent emission lines with no P Cygni profiles typical of other types.

During the years the improved observational capabilities and quality of the obtained data showed an unexpected diversity of SN properties.

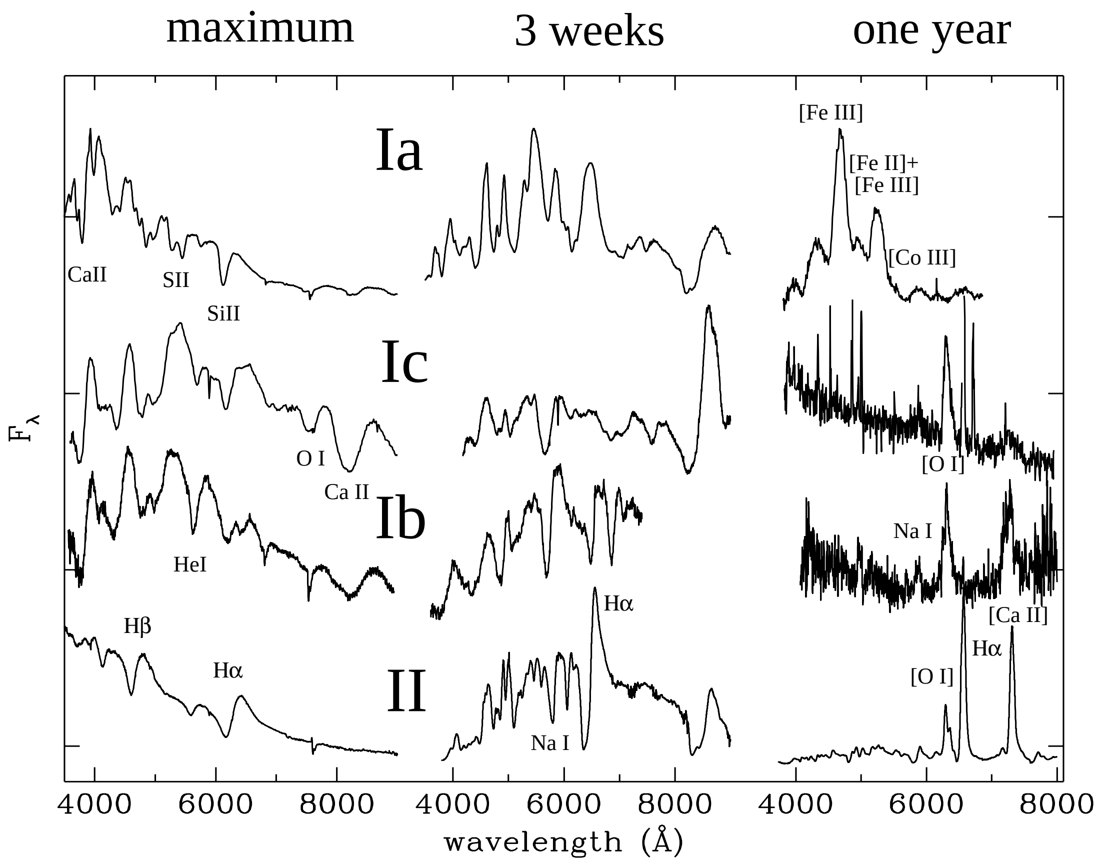


FIGURE 1.2– The spectra of the main SN types at maximum, three weeks and one year after maximum (from Turatto 2003).

1.3 General properties of Supernovae

After the explosion a large amount of material (ejecta) is expelled with a high velocity in the surrounding medium of the progenitor star. The mass of the ejecta varies from type to type and have values from one to tens solar masses. Within a short time the ejecta expands with a velocity proportional to the distance from the the center of the explosion (homologous expansion).

At the beginning the ejecta is dense and opaque, and the photosphere lays in the outermost layers, whose composition strongly depends on the SN type. As the expansion progresses, the density and temperature of the ejecta decreases and the photosphere recedes. These changes reflect on the spectral and luminosity evolution of the SN. Analysing the spectra and luminosity for a given phase and comparing the data to those obtained from theoretical models, it is possible to reconstruct the composition, velocity and density of the ejecta and find the explosion mechanism and SN progenitor.

The evolution is usually divided in two phases: photospheric and nebular, with a smooth transition between them. In the photospheric phase the high density of the ejecta determines the photosphere with a black body emission with temperature of 10000 - 20000 K. In a few months the optical depth of the expelled matter decreases and the innermost regions are exposed. The ejecta becomes gradually transparent to γ rays. The photosphere disappears and the SN enters in the nebular phase. In this phase

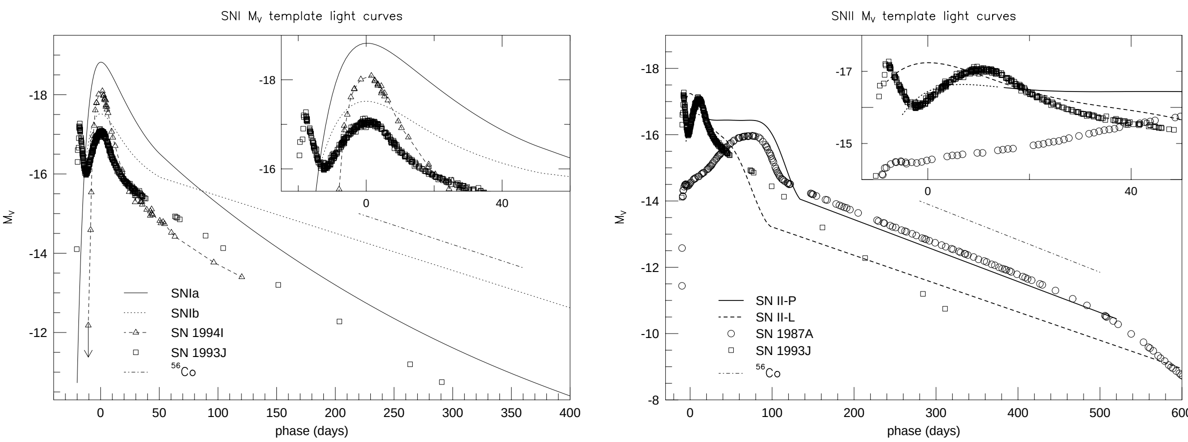


FIGURE 1.3– Photometric evolution of SNe Ia, Ib/c (left panel) and SNe II (right panel) (from Wheeler & Benetti 2000).

the energy is supplied by the radioactive decays.

Light curves

In general, the SNe light curves present a steep rise to the maximum light due to the rapid increase of the temperature and radius of the exploding star followed by a slower decrease. However, there is a big variety of shapes of the light curves (Figure 1.3), depending on the mass of the progenitor, explosion energy and also on the possible presence of circumstellar medium (CSM).

With the passing of time the differences caused by the various initial conditions are overwhelmed by the fast expansion of the ejecta. Several months after the explosion the light curves show a slow and gradual decline, with an exponential tail typical of radioactive decays (see Figure 1.3). The source of the energy in this period (nebular phase) is the radioactive decay of the elements synthesized during the explosion. The synthesized ^{56}Ni during the explosion decays to ^{56}Co, which in turns decays to ^{56}Fe. While the first reaction has an average half-life of 6.1 days and, therefore, influences the first phases of the evolution of the light curve, the second one has an average life of 77.2 days and determines the course of the light curve on longer temporal scales. At very late epochs (after about 1000 days) the decays of ^{57}Co and ^{44}Ti can also become important contributors.

In addition, depending on the mass of the ejecta, i.e. on its ability in trapping the γ rays produced in the radioactive decays, the slope of the light curve can be steeper (lower mass ejecta, SNe Ia, Ib/c) or flatter (greater mass of the ejecta, SNe II).

Spectra

In the photospheric phase the optical spectra of SNe are characterised by P Cygni lines superimposed on the photospheric continuum. The P Cygni (P-Cyg) profile has an emission peak near the rest wavelength of the line and a blueshifted absorption feature. The emission peak is formed by line scattering into the line of sight of photons emitted by the photosphere and would be symmetrical to the line center wavelength if not for the absorption. The absorption is formed by scattering out of the line of sight of photospheric photons emitted toward the observer. Since this occurs in front of the photosphere, the absorption is blueshifted.

At early times the ejecta velocity is high as well as the density, and the opacity is strong up to higher velocities. While the expansion proceeds, the photosphere and the region of line formation recede deeper into the ejecta. The P-Cyg line profile width thus decreases. The minimum of the absorption feature of weak lines tends to form near the photospheric velocity, thus weak lines can be used to determine the time evolution of the photospheric velocity.

The nebular phase, as already said, is powered by the radioactive decay of ^{56}Co (the result of explosion-synthesized ^{56}Ni decay). Without a photosphere, there is no continuum flux to be scattered out of the line of sight even if there are optically thick lines. Hence the characteristic line profile of the nebular phase is not a P-Cyg profile but an emission line that peaks near the rest wavelength.

1.4 Supernovae Ia

Type-Ia SNe are discovered in all types of galaxies, also in ellipticals (Barbon et al. 1999) and are not associated with arms of spirals as strongly as other types (Van Dyk et al. 1999). This, combined with the homogeneity of their properties, indicates that SNe Ia descend from old progenitors which are all in the same configuration at the explosion time.

It is believed that type-Ia SNe originate from the thermonuclear disruption of CO white dwarfs (WD) in binary systems (thus, SNe Ia are also called “thermonuclear SNe”). The explosion occurs when the WD accreting matter from the companion reaches the Chandrasekhar mass. The nature of the companion star is still not fully understood. Two favoured scenarios, in which the companion is a main sequence star or is another degenerate star, are still debated (Nomoto et al. 2003; and references therein).

As mentioned before, the spectra of type-Ia SNe are characterised by the lack of H lines at any phase. At early phases the spectra show broad P-Cyg profiles of Si II, S II, O I and Ca II lines. With age, metal lines (especially Fe and Co) become prominent, as the inner regions of the expanding envelope become visible. Around one month after maximum light Fe lines dominate the spectra. The nebular spectra of SNe Ia show strong [Fe II], [Fe III] lines.

The light curves of SNe Ia show a rather steep rise to maximum, which is reached around 17 - 20 days after the explosion. After a few days spent around maximum light the B luminosity suffers a fast linear decline dimming on by about 0.1 mag per day. After one month past maximum the decline becomes less steep and SN settles on the so-called exponential tail with an average slope of 0.015 mag/day. The V light curves have a similar behaviour, with the maximum light epoch 0.5-2 days after the B maximum. On the contrary, R light curves show a plateau after maximum light, which becomes a pronounced secondary maximum in the I light curves around 20-25 days after the primary maximum.

SNe Ia were believed to be a homogeneous group of objects, though the existence of significant differences among them were suggested too (e.g. Barbon et al. 1973). This was confirmed in 1991, when bright, slowly declining SN 1991T (Ruiz-Lapuente et al. 1992; Lira et al. 1998) and faint and fast declining SN 1991bg (Filippenko et al. 1992; Turatto et al. 1996) were discovered. Other under- and over-luminous objects have been found since then (Howell 2001). Moreover, other peculiarities in the type-Ia SN properties were found too: of them, SN 2000cx (Li et al. 2001) and SN 2002cx (Li et al. 2003) have shown anomalies in their spectroscopic and photometric behaviour which differentiate them from all other known SNe Ia.

In the '90s, intrinsic differences were identified in the luminosities of type-Ia SNe, which correlate with the early light curve shape, brighter objects having broader light curves than dimmer ones (Phillips 1993; Riess et al. 1996; Perlmutter et al. 1997; Phillips et al. 1999; Prieto et al. 2006b). This sequence was matched by spectroscopic variations attributed to changes in the effective temperatures, which were interpreted as variations in the mass of ^{56}Ni produced in the explosion (Nugent et al. 1995). These correlations have been employed to calibrate SNe Ia and use them as distance indicators up to cosmological distances. However, these relations do not fully account for the entire SN Ia diversity observed (Benetti et al. 2004b). Another important issue for the application of SNe Ia to cosmology is whether they evolve with redshift. Indeed, the lower metallicity of the progenitors at higher redshifts may result in systematic differences in brightness. Recent analysis on this issue do not seem to demonstrate such differences (Bronder et al. 2007).

1.5 Supernovae Ib/c

The characteristic spectral features of the SNe Ib are the absence of H and Si II lines and presence of He I. It was soon recognised that some objects did not show strong He lines (Wheeler et al. 1987) and the class of helium-poor type Ic was proposed.

Type-Ib and Ic SNe appear only in spiral type galaxies (Barbon et al. 1999) and have been associated with a parent population of massive stars, perhaps more massive than SNe II progenitors (Van Dyk et al. 1999). SNe Ib/c are thought to be produced by the core-collapse of very massive stars which have been stripped of their hydrogen (type-Ib) or both hydrogen and helium (Ic) envelope before the explosion. Therefore, at some epoch of their evolution, the SNe Ib/c are expected to interact with the interstellar material lost by the progenitor stars. In fact, they exhibit relatively strong radio emission, which is thought to arise from the SN shock interaction with a dense circumstellar medium (Chevalier 1982).

In order to investigate the physical differences between these two subclasses, the signatures of He were searched carefully. The He I λ10830 line in type-Ic was first found in the spectra of SN 1994I (Filippenko et al. 1995). Helium has been unambiguously identified also in the spectra of other type-Ic SNe. The He lines have expansion velocities much lower than other lines, indicating that the ejecta interacts with a dense shell of almost pure He originating from a stellar wind or mass transfer to a companion.

Weak absorption features attributed to H_α were first identified in the spectra of the type-Ib SNe 1983N and 1984L (Wheeler et al. 1994). Analyses of the spectra of a few other type-Ib SNe have suggested that detached H is frequently present in SNe Ib (Branch et al. 2002). The optical depths of H and He are not very high, so that modest differences in the He I line optical depths might transform type-Ib into type-Ic objects.

The SNe Ib/c are typically fainter than SNe Ia (at maximum, $M_B \simeq 18$, with a larger dispersion, Wheeler & Benetti 2000; Richardson et al. 2002). The light curves of type-Ib/c SNe have been divided in two groups depending on the luminosity decline rate (Clocchiatti & Wheeler 1997). However, the suggestion that type-Ic SNe include both fast and slow decliners while Ib seem to prefer slow decliners has been challenged by the existence of SNe Ib with fast light curves, e.g. SNe 1999I and 1991D.

Type-Ic SNe have recently deserved large attention because of their relation to gamma-ray bursts (GRBs). Indeed, long-duration GRBs at sufficiently close distance have been related to bright, highly energetic SNe Ic. The first prototypical SN 1998bw associated to GRB980425 showed broad-line SN Ic features (Iwamoto et al. 1998). Other similar objects were later discovered, SN 2003dh/GRB030329 (Stanek et al. 2003) and SN 2003lw/GRB031203 (Malesani et al. 2004). Detailed analysis showed that these SNe require even more than 10^{52} erg energy, justifying the introduction of the term "hypernovae" (Iwamoto et al. 1998). They are believed to be the outcome of very energetic black hole forming explosions of massive stars (30-50 $M_{\odot}$) which synthesize large amounts of ^{56}Ni (0.3-0.5 $M_{\odot}$). Pronounced asymmetries in the explosions of type-Ic SNe are important issue in this context. Direct evidences of aspherical explosions come from the late-time observations of type-Ic SNe (Mazzali et al. 2005b), as well as from the large polarisations measured for them (Leonard & Filippenko 2005).

1.5.1 Supernovae IIb

A few objects have been found to have early time spectra similar to type-II (i.e. with prominent H lines) and late time spectra similar to type-Ib/c SNe. For this reason they have been called type-IIb SNe. The first SN IIb was SN 1987K (Filippenko 1988), but the best studied example, and one of the best studied SNe ever, was SN 1993J in M81 (e.g. Barbon et al. 1995). In addition to SNe 1987M and 1993J, few other similar objects have been discovered (SNe 1996cb, 2001gd, 2001ig).

While the early spectrum of SN 1993J was almost featureless with a blue continuum and broad H and He I λ5876 lines typical of SNe II, already three weeks later it displayed progressively stronger He I $\lambda\lambda$5876, 6678 and 7065 lines characteristic of SNe Ib. The light curve of SN 1993J was unusual with a narrow peak followed by a secondary maximum. After another rapid luminosity decline around 50 days past the explosion, the light curve settled into an almost exponential tail with a decline rate faster than normal SNe II and similar to that of SNe Ia.

The progenitor stars of SNe IIb are expected to have lost most of their mass before explosion. This scenario is supported by a few observational properties: (1) the nebular spectra of SN 1993J show, at late time, Balmer emission lines of H with boxy profiles, consistent with the interaction with circumstellar material lost by the progenitor; (2) circumstellar gas in proximity to the exploding star was also revealed through the detection of narrow coronal lines persisting for a few days after the explosion (Benetti et al. 1994); (3) the luminosity evolution closely resembles that of SNe Ib, with a steep post-maximum decline rate typical of explosions with low mass ejecta.

These SNe transforming from type II to type Ib/c constitute the previously missing link between envelope retaining and envelope stripped SNe.

1.6 Supernovae II

Type-II SNe are characterised by the obvious presence of H in their spectra. They avoid early type galaxies (Barbon et al. 1999) and are strongly associated with regions of recent star formation (Van Dyk et al. 1999). SNe II display a wide variety of properties both in their light curves (Patat et al. 1994) and in their spectra (Filippenko 1997) and represent core-collapse (CC) explosions occurring in progenitor stars still retaining the H envelopes. Three major classes are often considered: type-II Plateau (SNe IIP) with flat light curves in the few months, type-II Linear (SNe IIL) with rapid, steady decline in the same period and the narrow-lined SNe II (SNe IIn), dominated by emission lines with narrow components, sign of energetic interaction between the SN ejecta and the CSM. The properties and mass of the progenitor star and the environment in which the SN explosion occurs are the main factors determining the display of type-II SNe, thus, modelling the observations helps to identify the progenitors. Another approach to this key issue is based on the direct detection of progenitor stars on high quality archive images obtained before the SN explosion (Smartt 2002; Van Dyk et al. 2003).

type-IIL SNe

SNe IIL are characterised by light curves showing a linear, uninterrupted decline of luminosity after maximum, probably because of the relatively low mass envelope. The absolute magnitude is similar to that of SNe Ib/c, even if with a slightly smaller scatter, as reported by Richardson et al. (2002). From $\sim$150 days after the explosion the light curves settle onto an exponential decline: this behaviour is consistent with constant trapping of the energy release of the radioactive decay of ^{56}Co to ^{56}Fe.

The spectra are dominated by H Balmer lines; He I lines are visible only for a few days after the explosion, then disappear and other lines (e.g. Na I, Ca II, Fe II, Sc II, Ba II) become prominent during the late photospheric phase. The nebular spectra show strong H I, [O I], Ca II, [Ca II] and [Fe II] emission lines.

The spectral and photometric behaviour is consistent with the core-collapse explosion of moderately massive stars (8-10 $M_{\odot}$), which eject low-mass envelopes (1-2 $M_{\odot}$, Branch et al. 1990). The envelope masses are smaller than those ejected by the SNe IIP, but larger than those of SNe IIb.

type-IIP SNe

SNe IIP constitute a very heterogeneous class of CC SNe, whose light curves show different characteristics both in shape and luminosity at maximum. The average absolute magnitude at maximum of SNe IIP is fainter than that of SNe IIL, but has a very large dispersion (σ = 1.12, Richardson et al. 2002). After maximum, the luminosity declines for a few days, until it reaches the plateau, a period of constant luminosity. After this, the light curve shows an evolutionary path similar to that of SNe IIL.

Despite the photometric differences, the spectroscopic evolution of type-IIP SNe closely resembles that of SNe IIL. The spectra have the same lines and a similar evolution, even if the absorption features in the photospheric spectra of plateau SNe are possibly stronger than those observed in the spectra of type-IIL SNe.

SNe IIP are thought to be produced by the explosion of stars spanning a very large range of masses which probably did not suffer significant mass loss phenomena before the explosion. Therefore the study of SNe IIP, not affected by phenomena of ejecta-CSM interaction, provides important information on the nature of the progenitor stars.

type-IIn SNe

A number of peculiar SNe II have been grouped into the of SNe IIn (“n” denoting narrow emission lines, Schlegel 1990). The spectra of these objects have a slow evolution and are dominated by strong H Balmer emission lines without the characteristic broad absorptions. The early time continua are very blue, He I emission is often present and, in some cases, narrow Balmer and Na I absorptions are visible corresponding to expansion velocities of about 1000 km s^{-1} (Pastorello et al. 2002). Unresolved forbidden lines of [O I], [O III] and of highly ionised elements such as [Fe VII] and [Fe X] are sometimes present. What we observe in these objects are the results of the interaction between ejecta and CSM, rather than the SN itself. The interaction of the fast ejecta with the slowly expanding CSM generates a forward shock in the CSM and a reverse shock in the ejecta. This source of energy largely dominates (sometimes for many years) over the usual sources powering the energy output of other SN types.

The best studied object of this class is SN 1988Z, detected also in radio and X-rays (Turatto et al. 1993). This object is considered the prototype of this class, although a common evolutionary path for these SNe does not really exist. SNe IIn are a heterogeneous group of CC SNe whose properties are determined by the distribution of the CSM around the SN, the amount of material and its density.

1.7 The current classification scheme and its problems

After the first classification of SNe, the taxonomy of SNe has been progressively developing. With increasing amount of observational data new types of SNe have been introduced, some have been dismissed, others remained in use. Also, the approach to the SN taxonomy was changed. While in the initial stage the classification was based on the recognition of the observational characteristics, later the idea of the classification has been refined: it had to reflect the nature of SNe, having as a basis of classification the intrinsic, physical differences among various SNe. At the beginning of this decade the SN classification scheme was already complicated, with many existing SN classes (see Turatto 2003; Wheeler & Benetti 2000).

1.7.1 The consolidated scenario

In the previous section I presented the consolidated scenario with types and subtypes (see Figure 1.4). It is widely accepted that the SNe result from two major explosion mechanisms, the gravitational collapse of the stellar nucleus (core-collapse) and the thermonuclear runaway.

The core collapse occurs in massive stars (M $\geq 8M_{\odot}$) at the end of a series of central nuclear burnings which end up with the formation of an iron core, and results in the formation of a compact remnant, a neutron star or a black hole. The different configurations of the progenitors at the moment of the explosion, the different energetics associated to the event and the possible interaction of the ejecta with CSM produce a large variety of displays.

The thermonuclear disruption of CO WDs, which have reached the Chandrasekhar mass limit accreting matter from a companion in a binary systems, produces type-Ia SNe. Whether the donor is another degenerate star or a main sequence star us still debated.

In the following section I discuss the recent results that challenge the consolidated scenario.

1.7.2 New challenges to the consolidated scenario

As mentioned in Section 1.1, in the last two decades (after the appearance of SN 1987A) the number of discovered SNe had an unprecedented growth. The improved monitoring capabilities and quality of

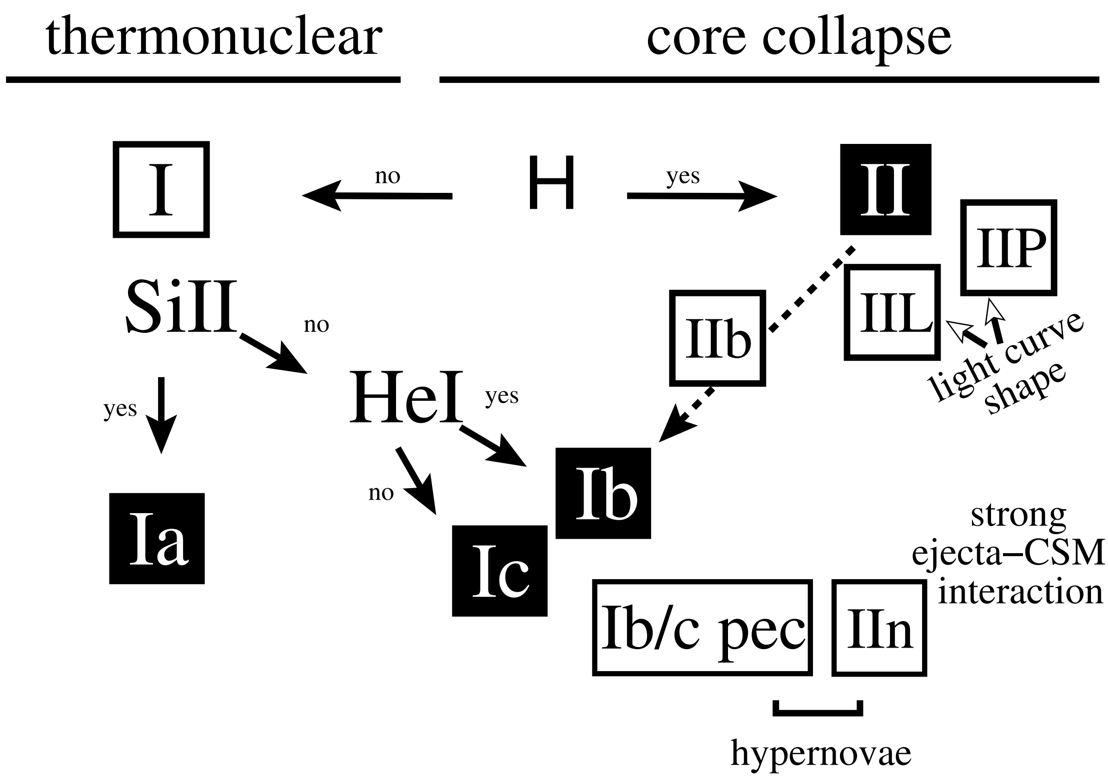


FIGURE 1.4– The consolidated scenario: type-Ia SNe come from the thermonuclear explosion of accreting WD. Other SN types are associated with the core-collapse of massive stars. Also hypernovae, that are the result of explosion of some Ib/c and IIn SNe with explosion energies > 10^{52} are reported on the scheme (from Turatto 2003).

the observations (signal-to-noise ratio, resolution, wavelength coverage, etc) brought to an unexpected diversification of the properties of SNe. As a consequence, we are discovering new common properties and differences among the objects of the consolidated types. In addition, new unprecedented objects appeared, opening new unexpected scenarios for the explosions.

SNe Ia

The CO WD Chandrasekhar-mass explosions well explain the main observational properties of these objects and their overall similarity. However, the Chandrasekhar mass scenario has been recently challenged by SN 2003fg, a SN Ia with usual spectral behaviour, relatively low expansion velocity, but high luminosity (2.2 times more luminous than normal). SN 2003fg did not obey the empirical relations (see Section 1.4) between the light curve shape and the luminosity at maximum. Objects like this, though rare, may contaminate the searches of high-z SNe Ia for cosmology. The progenitor mass was estimated to be $2.1M_{\odot}$ (i.e. a *super-chandra* scenario, Howell et al. 2006), which might be formed by the merge of two massive WDs. This hypothesis has, however, been confuted by Hillebrandt et al. (2007).

Based on the analysis of the photometric and spectroscopic properties of a sample of 26 objects Benetti et al. (2005) have identified three subclasses of SN Ia with distinct physical properties. The main characterising parameter is the gradient of expansion velocity of the photosphere. The subclasses are as follows: (1) *faint* SN Ia (similar to SN 1991bg), fast decliners both in luminosity and expansion velocity, with typically low expansion velocities and occurring in early-type galaxies; (2) high- (*HVG*) and (3) low-velocity (*LVG*) gradient SN Ia, that include normal objects, although the LVG group also includes all the brightest, slow declining SNe (like SN 1991T). More peculiar objects, like SNe 2000cx and 2002cx (see also Section 1.4) were not included in the above analysis.

Several attempts focused on the detection of CSM in the progenitor systems of SNe Ia have been carried out. In this context a remarkable cases are those of the SN 2002ic and 2005gj, which have shown pronounced H emission lines. These lines have been interpreted as a sign of very strong interaction between fast SN ejecta and slow CSM (Hamuy et al. 2003b; Aldering et al. 2006). However, Benetti et al. (2006b) show that SN 2002ic (and SN 2005gj, Benetti et al., 2008, in preparation) actually was a type-Ic SN, i.e. that the progenitor star was massive. In this scenario the observed interaction with dense CSM is predictable consequence of the intense mass-loss activity of the progenitor. See also Section 4.3 of this thesis for more information on SN 2002ic.

SNe Ib/c

As already described (Section 1.5), type-Ib/c SNe have recently deserved large attention due to their association to GRBs and this relation led to the introduction of *hypernovae*. In addition to the cases of hypernova-GRB connection, there are a number of *broad-line SNe Ic* for which the accompanying GRB has not been detected, e.g. SNe 2002ap (Mazzali et al. 2002), 2003jd (Valenti et al. 2007). These SNe seem to have smaller luminosity, mass of the ejecta and explosion energy than the GRB-SNe, but it is not clear whether the non-detection of the GRB is a geometric effect due to asymmetries or an intrinsic property of the explosion.

SNe II

SN IIP have been subject of extensive analysis by Hamuy (2003), who pointed out a continuum in the properties of these objects and revealed several relations linking the observables and the derived physical parameters, with more massive progenitors producing more energetic explosions. An independent analysis by Pastorello (2003), performed on a more extended sample, confirmed the continuity in the physical properties over a very broad range. In particular, the group of *faint, slowly expanding* SNe with characteristics similar to SN 1997D (Turatto et al. 1998; Pastorello et al. 2004), appears as the low luminosity tail of the distribution of SN IIP properties.

The existence of *ultrafaint* core-collapse SNe, even fainter than SN 1997D, has been suggested. This objects are still undetected, but there are at least two examples of nearby, long duration GRBs, for which no optical counterpart brighter than M_V = -13.5 has been identified (Della Valle et al. 2006; Gal-Yam et al. 2006; Fynbo et al. 2006).

Extremely massive SN progenitors

In the autumn of 2006 two remarkable SNe exploded, which shed light (or confused our scanty hypothesis) on the final fate of the extremely massive stars.

SN 2006gy, with its extremely high luminosity $M_{V,max} \sim$ -22, slow rise to maximum ($\sim$70 days) and total amount of released energy ($\sim 10^{51}$ erg), became an unprecedented event. The huge amount of radiated energy might be explained only with an explosion of a very massive star, no matter if the light curve is powered by CSM interaction of by radioactive decay of ^{56}Ni (Smith et al. 2007). As proposed, the explosion mechanism was the pair-instability collapse. Subsequent studies still in progress seem to exclude such a possibility on the base of the large but not huge mass of ^{56}Ni produced (Agnoletto et al., 2008, in preparation). Another viable possibility has been proposed by Woosley et al. (2007). See Section 4.2 for a more detailed discussion on SN 2006gy.

Shortly after SN 2006gy, another object, SN 2006jc appeared with a very peculiar optical display. The spectrum was that of a H-poor event, with broad SN Ic features and much narrower He emissions. Therefore, it has been proposed (Pastorello et al. 2007b) that it should be more properly classified as a *type-Ibn* SN. Type-Ibn SNe appear to be rather normal type-Ib/c SN explosions which occur within a He-rich circumstellar environment. SNe Ibn are therefore likely produced by the explosion of Wolf–Rayet progenitors still embedded in the He-rich material lost by the star in recent mass-loss episodes, which resemble known luminous blue variable eruptions. The evolved Wolf–Rayet star could either result from the evolution of a very massive star or be the more evolved member of a massive binary system (Pastorello et al. 2008).

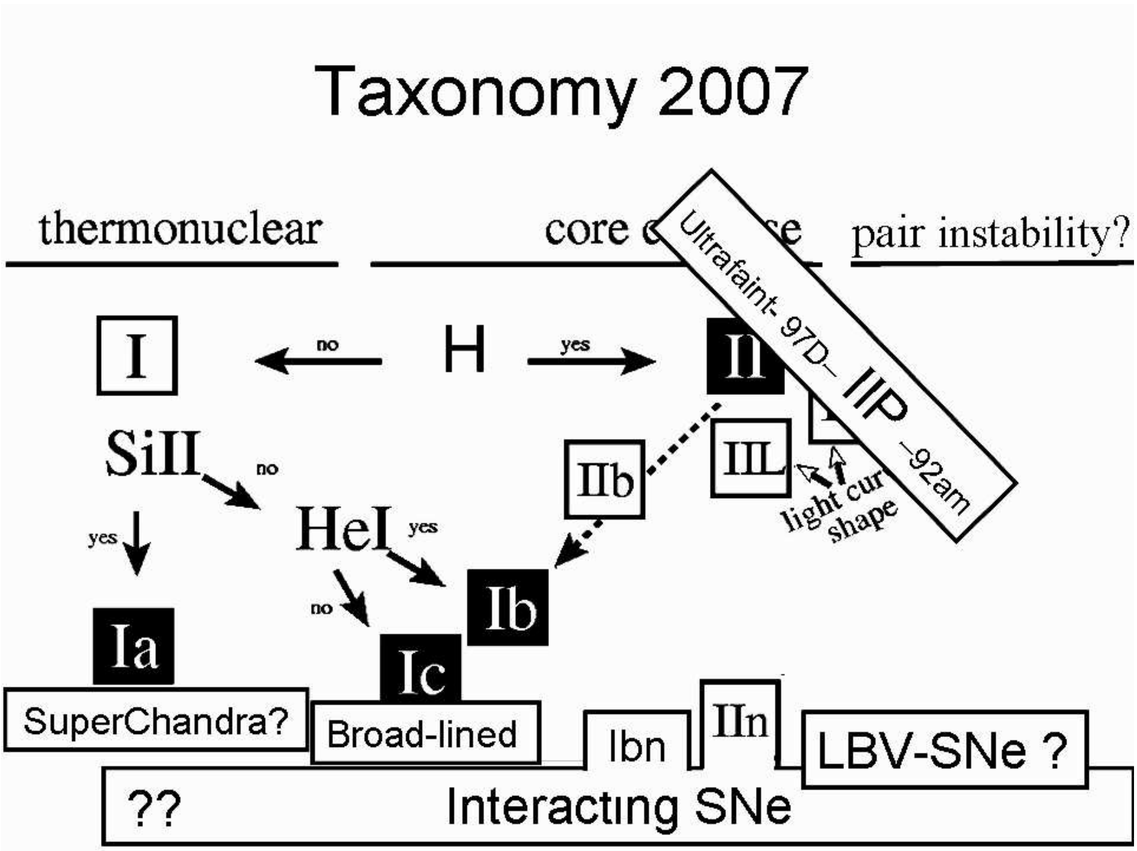


FIGURE 1.5– The 2007 version of the classification of SNe. To be considered as the updated version of the plot in Figure 1.4 (from Turatto et al. 2007).

1.7.3 The new "provisional" classification scheme

In the light of the recent issues discussed in Section 1.7.2, Figure 1.5 from Turatto et al. (2007) shows the updated version of the classification scheme published in Turatto (2003) (see Figure 1.4).

It is evident that the classification scheme is ambiguous and non-exhaustive, it causes many objects to be classified as "peculiar". Among so many SN classes and subclasses only the most experienced specialists are able to orientate themselves. Thus the classifications of not obvious events might sometimes be subjective or biased.

A classification of this kind is unsatisfactory and is useful just to guide an unexperienced reader through the zoo of SNe, waiting for a more physical classification of SNe.

1.8 Motivation of this Thesis

"... notoriamente no hay clasificación del universo que no sea arbitraria y conjetural. La razón es muy simple: no sabemos qué cosa es el universo."
Jorge Luis Borges, *El idioma analítico de John Wilkins*[*]

The diversity of SNe will increase, as continuously growing amount of higher quality data on SNe will become available. This will cause the astronomers to refine the SN classification scheme, and it will take long time until a robust classification, based on solid physical criteria will be found.

In the previous sections I presented the most modern but still unsatisfactory SN taxonomy, highlighting the recent challenges impacting our already shaky classification scheme. This confusing picture, however, does not anyhow underestimate the extreme importance of classification of SNe. Ordering physical objects in groups on the basis of their observed characteristics is the first, most essential issue for our understanding of their nature, their intrinsic physical properties and the processes governing their evolution. This is the final aim of the classification of SNe. However, in the case of transient events, the classification has another immediate goal. These classifications are used to select interesting targets for the extensive follow-up observations. The success of extensive and time-consuming observational campaigns on SNe depends crucially on the prompt classification of newly discovered objects.

At the moment, few experts from several SN groups are capable of satisfactory identification of SNe, though this sort of classification is biased by subjective (read "personal") convictions. In a situation like this, where the classification criteria are not complete and contain subjective elements, a way out and also a conservative approach for SN classification is via comparison with other SNe. Such a comparison, performed in an automatic and quantitative manner, should be able to sort out the objects with similar properties (that is, classify them) and is objective (since it is not contaminated by subjective opinions). The comparisons should be done on the basis of spectra, the observables which provide the most information on nearby SNe and are relatively easy to collect.

The motivation of the work presented in this Thesis lies between the above lines, aiming to prepare

[*] "... there is no classification of the Universe not being arbitrary and full of conjectures. The reason for this is very simple: we do not know what the universe is." Jorge Luis Borges, *The analytical language of John Wilkins*

a method of objective classification of SNe. In this Thesis I describe the development of such tools and their various applications in the SN research performed.

To perform this work, an archive of SN spectra was needed. This is one of the crucial components of an objective spectral classification, since a large archive with spectra of numerous SNe spanning the wide variety of SN properties is a prerequisite. Fortunately, from early '90s Padova SN group has been collecting the available SN spectra in an extensive archive, one of the largest ones in the world. Using the archive spectra, the templates needed for the comparison are created.

The second important component, needed for objective classification, is the software doing the spectra comparison. The development of Padova SN spectra comparison tool (PASSPARTOO) and its algorithm are presented and discussed extensively.

Two above mentioned ingredients (the template spectra and the comparison software) are put together, and their combination is used to study and classify the SNe. We demonstrate the utility of the software with a sample of SN spectra obtained by a large research network, European Supernova Collaboration. A SN classification program at Telescopio Nazionale Galileo, where the classification software is largely used, is then presented and discussed. Further, other applications of the comparison tools are also shown.

2

Padova - Asiago Supernova Archive

As already told in the previous chapter, a crucial part for an automated spectral classification is the an extended archive of spectra. I used the spectra from Padova - Asiago Supernova Archive as templates for comparison. In this chapter I present the archive, its history and the major projects that enrich it. Further, the archive contents are described and the statistics on the data, their amount and organisation information are provided. I also present the tools developed by me, for the archive data homogenisation and collection. A brief presentation of the group's SN light curves archive, SN catalogue and an overview of public SN spectra archives conclude this chapter.

2.1 History

With the aim to collect and update homogeneous samples of photometric and spectroscopic SN data, already at the beginning of '90s the Padova SN group has organised the available observational material into an archive (Barbon et al. 1993). At that moment, the data were mainly coming from observational programs carried out at Asiago and ESO (Chile). Also, material obtained from the digitalisation of photographic plates taken at Asiago in the past years (see, for instance, Benetti 1991), data occasionally collected at other sites and data from literature were included. Thereafter, the archive was continuously enriched by the members of the group in the course of many short and long-term projects devoted to the study of the physical properties of SNe.

The followings are the major long-term programs that enriched the archive.

- ✔ Long-term SN monitoring at Asiago. From early '90s up to now the Padova SN group carries out SN monitoring programs exploiting the observational facilities at the Asiago observatory. Programs devoted to the classifications and follow up observations of SNe have been the major contributors of the archive.

- ✔ Two ESO Key projects. In '90s, the group leaded two Key projects dedicated to the study of SNe at ESO. A total amount of 60 and 40 nights has been granted to the projects 4-004-45K and 4-004-51K, respectively. Using the 3.6m, 2.2m and NTT telescopes at La Silla, several tens of SNe of different types have been monitored. Consequently, the archive has been considerably enriched with both spectroscopic and photometric data.

- ✔ European Supernova Collaboration (ESC)*. The ESC is an European Research Training Network (RTN) funded by the European Community for 4 years (2002-2006) and formed by the SN research groups (nodes) from 10 European Institutions. Padova SN group was one of the nodes of the collaboration. The collaboration was born with the goal to improve our understanding of type-Ia SN physics through a complete and detailed set of homogeneously-acquired observations and a consecutive realistic models. For the first time homogeneous sets of light curves and spectra for a rather large sample of SNe Ia were obtained through systematic and targeted observations by a coordinated action of all major european SN research groups. In total the ESC have tripled the number of type-Ia SNe observed starting well before maximum light and followed with very good time and wavelength coverage, both spectroscopically and photometrically. The ESC performed a detailed spectroscopic and photometric monitoring of 15 nearby SNe Ia (plus 1 SN Ic). During the past few years the data of several SNe observed by the ESC have already been contributed to the archive and the remaining data will be archived soon, so the archive will contain the entire ESC dataset. Finally, besides the many papers published and to be published by the collaboration, several tens of IAU-Circulars were published in the past years, mostly giving fast identifications and age of nearby SNe. See the Section 4.1 for a more detailed presentation and discussion on this issue.

- ✔ Long-term SN program at Telescopio Nazionale Galileo (TNG)†. From the August 2007 the Padova SN group has started a long-term observational program called "The contribution of Supernovae to the cosmic chemical evolution" at TNG. A total of ∼14 nights of observational time will be granted to the program for each semester for a total of two years of granted time. A number of nearby SNe has already become targets of this program and the group performs their detailed follow-up observations both in optical and infrared bands. Thus also this project will be a source of major enrichment of the archive. An integral part of the project is a SN classification program (9 hours in ToO mode per run) aiming on fast classification of newly discovered objects and their consecutive selection for further observations.

The archive was divided in two parts: the Asiago Supernova spectra Archive (ASA) and the Asiago LIght Curve Environment (ALICE). Also, the Asiago Supernova Catalogue (ASC) can be considered an important part of the archive. In the following sections I present in a detailed manner the spectra archive and, briefly, also the light curves archive and the ASC.

2.2 The Asiago Supernova spectra Archive (ASA)

ASA collects 2708‡ wavelength and flux calibrated spectra of 388 SNe of all types. Tables 2.1-2.4 list the ASA SNe, their types and redshifts, number of spectra per object and their phase range. The types of

*http://www.mpa-garching.mpg.de/∼rtn

†http://www.tng.iac.es

‡the reported numbers and statistics regarding the Archive are obtained for October 2007

TABLE 2.1– The ASA SNe and spectra

SN	Type	Redshift z	Spectra number	Phase range days	SN	Type	Redshift z	Spectra number	Phase range days
1937C	Ia	0.0011	5	8 – 39	1991K	Ia	0.017	3	70 – 122
1969L	IIP	0.0016	7	2 – 61	1991L	Ib/c	0.03	1	13
1974G	Ia	0.0024	1	9	1991M	Ia	0.0072	9	1 – 147
1978K	II	0.0015	2	7683,7687	1991N	Ic	0.0033	5	5 – 282
1979B	Ia	0.0032	5	9 – 47	1991S	Ia	0.055	2	16,19
1979C	IIL	0.0053	24	5 – 223	1991T	Iapec	0.0058	35	-12 – 1785
1980K	IIL	0.0002	19	2 – 95	1991ah	IIn	0.037	3	62 – 84
1980N	Ia	0.006	1	31	1991al	II	0.01	4	20 – 28
1981B	Ia	0.006	22	-3 – 356	1991ar	Ib	0.0152	2	14,30
1982B	Ia	0.0074	2	3,28	1991bb	Ia	0.0266	1	45
1983G	Ia	0.0039	6	-1 – 8	1991bc	Ia	0.0214	2	19,49
1983N	Ib	0.0017	6	-8 – 228	1991bd	Ia	0.0127	2	16,46
1983U	Ia	0.0039	1	14	1991bg	Iapec	0.003	21	1 – 203
1983V	Ic	0.0055	3	-9 – -4	1991bj	Iapec	0.0182	1	2
1984A	Ia	-0.0009	12	-7 – 54	1992A	Ia	0.0062	35	-6 – 406
1984E	IIL	0.0041	1	3959	1992B	Ia	0.055	1	13
1984L	Ib	0.0051	3	10 – 61	1992C	II	0.0101	9	15 – 455
1985L	IIL	0.0029	2	13,203	1992D	IIn	0.05	2	7,33
1986E	IIL	0.0037	5	23 – 5907	1992E	Ia	0.06	2	9,9
1986G	Iapec	0.0018	53	-6 – 324	1992G	Ia	0.0053	4	-2 – 35
1987A	IIpec	0.0011	112	-76 – 5014	1992H	II	0.006	29	10 – 403
1987B	IInL	0.0085	2	6,7	1992K	Iapec	0.0104	6	45 – 45
1987K	IIb	0.0027	7	0 – 208	1992O	Ia	0.037	4	25 – 25
1988A	IIP	0.0051	5	3 – 444	1992al	Ia	0.0146	1	61
1988G	Ia	-1.0	1	29	1992ao	II	0.0122	25	4 – 1382
1988H	IIP	0.0066	5	21 – 874	1992av	Ia	-1.0	1	9
1988L	Ib	0.0062	8	11 – 138	1992ay	IIn	0.062	1	13
1988Z	IIn	0.0222	21	115 – 3773	1992ba	II	0.0041	3	3 – 150
1989B	Ia	0.0024	70	-6 – 348	1992bb	Ia	-1.0	2	31,31
1989C	IIP	0.0063	3	3 – 58	1992bm	II	0.05	1	-315
1989M	Ia	0.0051	12	20 – 421	1993H	Ia	0.0241	5	1 – 416
1990B	Ic	0.0075	20	5 – 148	1993J	IIb	-0.0001	39	1 – 1264
1990E	IIP	0.0041	21	13 – 537	1993K	II	0.0091	13	31 – 354
1990H	II	0.0053	8	2 – 27	1993L	Ia	0.0064	15	16 – 378
1990I	Ib	0.0097	24	0 – 357	1993M	Ia	0.0901	2	18,18
1990K	II	0.0053	21	5 – 475	1993N	IIn	0.0098	11	32 – 655
1990M	Ia	0.0088	8	1 – 55	1993S	II	0.032	2	33,90
1990N	Ia	0.0033	6	-14 – 246	1993T	Ia	0.0881	1	33
1990Q	II	0.0064	3	3 – 299	1993W	II	0.018	2	2,6
1990S	IIn	0.0256	1	4	1993ad	II	0.0172	11	3 – 326
1990U	Ic	0.0079	25	-3 – 367	1993ae	Ia	0.019	1	10
1990W	Ib/c	0.0049	10	1 – 3995	1993af	Ia	0.0033	7	-304 – 318
1990aa	Ic	0.0166	20	7 – 141	1993aj	Ia	0.0751	1	14
1990ah	II	0.0175	1	-84	1994D	Ia	0.0015	42	-11 – 373
1990aj	Iac	0.0053	5	42 – 82	1994I	Ic	0.0015	50	-6 – 146
1991A	Ic	0.0107	8	5 – 96	1994L	II	0.0068	17	31 – 356
1991D	Ib	0.0418	14	5 – 78	1994M	Ia	0.0232	3	15 – 15
1991E	II	0.024	1	4	1994N	II	0.0098	8	0 – 265
1991H	II	0.018	1	1	1994R	II	0.007	1	10
1991I	II	0.036	1	2	1994S	Ia	0.0152	1	-4

TABLE 2.2– The ASA SNe and spectra (continuation)

SN	Type	Redshift z	Spectra number	Phase range days	SN	Type	Redshift z	Spectra number	Phase range days
1994U	Ia	0.0044	1	0	1997D	IIpec	0.0052	16	-1 – 383
1994Z	II	0.0118	13	2 – 365	1997X	Ic	0.0037	22	5 – 101
1994ae	Ia	0.0043	13	-6 – 531	1997Y	Ia	0.016	4	31 – 32
1994ai	Ic	0.005	8	4 – 70	1997Z	II	0.0086	5	2 – 7
1994aj	II	0.032	30	43 – 540	1997ab	IIn	0.0125	6	357 – 777
1995D	Ia	0.0066	8	-6 – 364	1997bp	Iapec	0.0083	12	-1 – 414
1995F	Ic	0.0051	5	10 – 260	1997bq	Ia	0.0094	1	18
1995G	IIn	0.0163	21	2 – 942	1997br	Iapec	0.0069	13	-4 – 404
1995H	II	0.0047	6	-10 – 247	1997bs	IIn	0.0024	1	14
1995J	II	0.0099	1	30	1997bt	II	0.0648	1	16
1995M	Ia	0.052	1	38	1997by	Ia	0.0453	1	3
1995N	IIn	0.0062	63	4 – 3374	1997cn	Iapec	0.0167	3	3 – 78
1995P	Ia	0.056	1	22	1997cr	II	0.0771	2	8,8
1995R	Ia	0.0237	1	7	1997cw	Iapec	0.0176	9	44 – 106
1995T	Ia	0.056	1	8	1997cy	IIn	0.0642	15	8 – 635
1995U	Ia	0.0556	1	5	1997dc	Ib	0.0115	2	6,32
1995V	II	0.0051	16	1 – 402	1997dd	IIb	0.0152	1	17
1995W	II	0.0113	21	12 – 780	1997de	Ia	0.0129	1	25
1995X	II	0.0052	1	28	1997dh	Ic	0.05	1	4
1995Z	II	0.0158	2	88,91	1997dq	Ib/cpec	0.0032	5	6 – 428
1995aa	IIn	0.19	1	23	1997ds	II	0.0094	1	8
1995ac	Iapec	0.05	8	0 – 43	1997du	II	0.02	2	26,35
1995ad	II	0.0061	23	7 – 508	1997ef	Ib/cpec	0.0118	8	4 – 102
1995ae	Ia	0.0689	1	10	1997eg	IIn	0.0089	4	76 – 547
1995ag	II	0.0049	2	33,207	1997ei	Ic	0.0107	1	25
1995ak	Ia	0.0227	3	-1 – 19	1997ej	Ia	0.0223	2	32,37
1995al	Ia	0.0051	10	-3 – 166	1998A	IIpec	0.007	10	18 – 397
1995bb	Ic	0.0058	1	18	1998E	IIn	0.008	1	374
1995bd	Iapec	0.0154	3	16 – 19	1998R	II	0.0067	1	36
1996A	II	0.033	7	10 – 39	1998S	IIn	0.0028	5	7 – 489
1996D	Ic	0.0158	5	9 – 214	1998T	Ib	0.0101	3	3 – 27
1996L	IIL	0.033	16	9 – 336	1998V	Ia	0.0174	1	12
1996M	II	0.02	4	3 – 61	1998W	II	0.0119	2	6,14
1996W	II	0.0055	13	8 – 309	1998bn	Ia	0.0061	1	360
1996X	Ia	0.0068	17	-4 – 298	1998bp	Ia	0.0106	2	27,346
1996Z	Ia	0.0076	3	5 – 269	1998bu	Ia	0.0031	12	-7 – 681
1996ae	IIn	0.0052	5	7 – 23	1998bw	Ic	0.0085	34	-9 – 376
1996al	II	0.0061	48	1 – 2155	1998ce	II	0.0084	1	10
1996an	II	0.0047	18	3 – 487	1998cg	Ia	0.119	1	29
1996aq	Ic	0.0053	17	2 – 270	1998co	Ia	0.0182	1	31
1996ar	Ia	0.06	1	3	1998cv	Ic	0.027	1	28
1996as	II	0.036	2	3,3	1998cx	Ia	0.0197	1	18
1996bl	Ia	0.036	1	-3	1998dg	Ia	0.0082	1	203
1996bo	Ia	0.0175	2	-6,49	1998dh	Ia	0.0089	4	8 – 58
1996bw	II	0.0181	3	7 – 22	1998dj	Ia	0.0137	2	4,52
1996bx	Ic	0.06	1	19	1998dk	Ia	0.0132	2	29,31
1996cb	IIb	0.0024	19	12 – 155	1998dl	II	0.0047	2	59,116
1996cc	II	0.0072	6	83 – 140	1998dm	Ia	0.0065	2	23,27
1997B	Ic	0.0104	18	1 – 385	1998dn	II	0.0013	2	43,95
1997C	Ia	0.0227	1	27	1998dq	Ia	0.0108	1	39

TABLE 2.3– The ASA SNe and spectra (continuation)

SN	Type	Redshift z	Spectra number	Phase range days	SN	Type	Redshift z	Spectra number	Phase range days
1998dt	Ib	0.015	7	19 – 125	2000P	IIn	0.0074	6	3 – 506
1998ee	IIpec	0.0497	1	116	2000bg	IIn	0.0245	1	4
1998es	Iapec	0.0105	3	-2 – 58	2000ck	IIpec	0.0268	1	5
1998et	IIn	0.0404	1	296	2000cm	Ia	0.0072	1	4
1998ew	II	0.0103	1	179	2000cn	Ia	0.0235	2	-8,86
1998fa	IIb	0.0244	5	25 – 77	2000cu	Ia	-1.0	1	2
1999E	IIn	0.026	17	8 – 449	2000cx	Iapec	0.0081	5	1 – 114
1999J	Iapec	0.0334	1	21	2000da	II	0.0244	1	19
1999P	Ib/c	0.06	2	6,7	2000db	II	0.0023	1	16
1999Z	IIn	0.0504	2	31,115	2000de	Ib	0.008	4	13 – 14
1999aa	Iapec	0.0149	3	13 – 50	2000dg	Ia	0.0385	1	6
1999ac	Iapec	0.0095	7	-6 – 391	2000dj	II	0.0158	2	7,8
1999as	Icpec	0.127	1	54	2000eo	IIn	0.0108	1	10
1999br	IIpec	0.0034	8	11 – 99	2000ev	IIn	0.0146	1	1
1999bv	Ia	0.0184	1	5	2000ew	Ic	0.0032	2	65,109
1999by	Iapec	0.0021	1	183	2000fc	Ia	0.42	1	9
1999cf	Ia	0.0244	1	13	2000fe	II	0.0141	1	11
1999cl	Ia	0.0071	3	16 – 297	2000fp	II	0.3	1	5
1999cn	Ic	0.0226	3	1 – 299	2001N	Ia	0.021	5	11 – 57
1999cw	Ia	0.0124	10	3 – 397	2001V	Ia	0.0151	3	13 – 54
1999cz	Ic	0.0072	1	15	2001X	IIP	0.0049	2	129,468
1999da	Ia	0.0123	1	60	2001bb	Ic	0.0158	4	18 – 74
1999dh	II	0.0108	1	22	2001bc	II	0.195	1	8
1999di	Ib	0.0164	3	9 – 40	2001bd	II	0.0961	1	10
1999dk	Ia	0.0152	6	-14 – 67	2001be	Ia	0.241	2	9,9
1999dn	Ib	0.0094	12	6 – 379	2001bg	Ia	0.0071	2	3,11
1999dq	Iapec	0.0145	1	-6	2001cz	Ia	0.0157	4	-1 – 29
1999eb	IIn	0.0181	7	5 – 88	2001dc	IIP	0.0071	3	41 – 86
1999ec	Iac	0.0092	1	6	2001dk	IIP	0.018	1	164
1999ee	Ia	0.0114	14	-9 – 41	2001dr	II	0.0239	1	11
1999el	IIn	0.0044	4	18 – 103	2001du	II	0.0055	1	16
1999em	IIP	0.0024	23	-2 – 635	2001ed	Ia	0.0165	1	7
1999et	II	0.0163	2	0,0	2001eh	Ia	0.0371	17	3 – 69
1999eu	IIpec	0.0042	4	5 – 43	2001ep	Ia	0.013	25	7 – 103
1999ex	Ib/c	0.0114	8	-1 – 13	2001fh	Iapec	0.013	2	3,14
1999ey	IIn	0.0931	2	4,25	2001fv	II	0.0049	2	66,68
1999ga	II	0.0047	4	40 – 441	2001fw	Ib	0.0295	1	7
1999ge	II	0.0188	1	10	2001ge	Ia	0.22	1	1
1999gi	IIP	0.002	2	49,173	2001gf	Ia	0.13	2	1,1
1999go	II	0.0148	2	5,6	2001gg	II	0.61	1	1
1999gt	Ia	0.274	3	13 – 13	2001gh	II	0.16	2	1,29
1999gu	II	0.147	2	13,13	2001gi	Ia	0.2	1	1
2000B	Ia	0.0191	2	10,19	2001gj	II	0.27	1	1
2000C	Ic	0.0127	5	17 – 34	2001ie	Ia	0.0308	1	4
2000D	II	0.0172	2	8,19	2001ig	IIb	0.003	1	188
2000E	Ia	0.0044	7	14 – 144	2001io	Ia	0.19	3	12 – 12
2000H	IIb	0.013	6	9 – 66	2001ip	Ia	0.54	3	12 – 1433
2000M	II	0.0103	1	5	2001is	Ib	0.0133	2	17,18
2000N	II	0.0133	2	5,9	2001it	II	0.0345	1	18
2000O	Ia	0.0235	2	4,9	2002A	IIn	0.0096	1	10

TABLE 2.4– The ASA SNe and spectra (continuation)

SN	Type	Redshift z	Spectra number	Phase range days	SN	Type	Redshift z	Spectra number	Phase range days
2002an	II	0.0129	1	14	2004dt	Ia	0.0195	33	-10 – 354
2002ap	Icpec	0.0021	38	-7 – 250	2004eo	Ia	0.0157	21	2 – 241
2002bh	II	0.0173	1	9	2004et	II	0.0002	5	58 – 263
2002bo	Ia	0.0043	28	-14 – 367	2004ex	IIb	0.0174	3	36 – 85
2002cl	Ic	0.072	2	14,14	2004gd	IIn	0.0174	1	39
2002cm	II	0.0871	2	14,14	2004go	Ia	0.0291	1	19
2002cn	Ia	0.302	2	14,14	2004gt	Ib/c	0.0055	2	24,163
2002co	II	0.318	1	14	2005G	Ia	0.0231	1	4
2002cr	Ia	0.0094	5	4 – 46	2005N	Ib/c	0.0163	1	3
2002cs	Ia	0.0157	1	2	2005W	Ia	0.0087	2	1,15
2002cv	Ia	0.0043	10	-5 – 26	2005ab	II	0.0154	1	4
2002dg	Ib	0.0467	1	15	2005au	II	0.0182	1	15
2002dj	Ia	0.0093	9	2 – 287	2005aw	Ic	0.0133	1	62
2002dm	Ia	0.0252	1	43	2005ay	IIP	0.0027	12	1 – 308
2002du	II	0.21	1	68	2005bl	Ia	0.0241	1	33
2002ej	II	0.0162	1	21	2005br	Ib	0.0103	1	58
2002eo	II	0.0204	1	11	2005bs	Ia	-1.0	1	36
2002er	Ia	0.0091	27	-11 – 582	2005cb	Ic	0.0105	1	12
2002gd	II	0.009	13	3 – 111	2005cf	Ia	0.0065	31	-12 – 77
2002hy	Ibpec	0.0127	1	3	2005cq	Ia	0.31	1	10
2002ic	Iapec	0.066	8	16 – 258	2005cs	IIP	0.0015	17	-1 – 222
2002ji	Ib/c	0.0049	1	5	2005ip	II	0.0071	6	3 – 95
2003G	IIn	0.0115	3	15 – 16	2006G	II/IIb	0.0168	1	25
2003J	II	0.0026	1	13	2006W	IIL	0.0159	1	2
2003L	Ic	0.0213	1	13	2006X	Ia	0.0053	2	1,9
2003M	Iapec?	0.0242	5	12 – 42	2006aj	Ib/c	0.033	16	-7 – 10
2003Z	II	0.0042	12	23 – 149	2006ao	II	0.0299	1	10
2003bg	Icpec	0.0044	1	4	2006ca	II	0.0089	1	2
2003cg	Ia	0.0041	40	-8 – 386	2006gi	Ib	0.0094	1	146
2003dt	Ia	0.0142	1	2	2006gy	IIn	0.0188	3	-31 – 106
2003du	Ia	0.0064	10	-11 – 72	2006gz	Ia	0.0236	17	-13 – 12
2003ei	IIn	0.0268	2	61,62	2006jc	Ib/cpec	0.0056	28	3 – 78
2003gd	II	0.0021	7	15 – 73	2006ov	IIP	0.0053	2	-39,79
2003gs	Iapec	0.0047	2	14,26	2007C	Ib	0.0056	1	12
2003hg	II	0.0143	1	4	2007F	Ia	0.0238	1	2
2003hn	II	0.0039	1	3	2007I	Ic	0.0216	1	28
2003ie	II	0.0023	1	3	2007R	Ia	0.0308	1	5
2003jd	Icpec	0.0188	13	0 – 29	2007T	II	0.0135	1	4
2004G	II	0.0053	1	2	2007af	Ia	0.0053	1	67
2004aq	II	0.014	1	8	2007bj	Ia	0.0166	1	2
2004aw	Ic	0.0158	32	1 – 261	2007bm	Ia	0.0062	5	2 – 28
2004dg	II	0.0045	1	2	2007bt	IIn	0.04	1	21
2004dh	II	0.0194	2	93,93	2007bw	IIn	0.14	1	32
2004dj	IIP	0.0004	5	133 – 157	2007fo	Ib	0.0094	1	7

SNe are reported following their designation in the ASC. The ASC contains the classification reported in the literature: either from dedicated papers or from IAUC-s. For a more detailed presentation of ASC see Section 2.4.

TABLE 2.5– The numbers of ASA spectra per object

Number of SNe	Number of spectra	Number of SNe	Number of spectra
308	1 – 9	148 (38.1%)	1
41	10 – 19	61	2
39	≥ 20	27	3

While a part of the ASA spectra have been presented in various papers dedicated both to studies of single SNe and to statistical analysis of SN properties, many of them have not been published so far. Some objects are present with single or few spectra in the ASA, because after their classification they have not been considered worth of further follow-up observations. Others have tens of spectra, since they have been targets of large observational campaigns. Table 2.5 shows the distribution of the ASA SNe on the basis of the number of spectra. In fact, a large fraction of SNe has less than three spectra.

TABLE 2.6– The number of ASA SNe per type

Type	Number of SNe	Type	Number of SNe	Type	Number of SNe
Ia	134	Ib	19	II	125
Ia-pec[1]	21	Ic	34	IIn	34
		Ib/c[2]	12	IIb	9

Notes:
[1] including objects like 1991T, 1991bg, 2000cx
[2] including hypernovae and peculiar objects like 1997dq, 2006jc

TABLE 2.7– The number of ASA spectra per types

Type	Number of spectra	Type	Number of spectra	Type	Number of spectra
Ia	811	Ib	129	II	833
Ia-pec	198	Ic	355	IIn	217
		Ib/c	83	IIb	82

Table 2.6 illustrates the type division of the ASA SNe. In the table, the Ia-pec group contains the 1991bg- and 1991T-like objects and also SN 2000cx. The type-II includes type-IIP, IIL events and the Ib/c contains hypernovae and peculiar objects like 1997dq, 2006jc. Table 2.7 lists the number of the ASA SN spectra of each type.

Almost all ASA spectra are of nearby SNe. 2662 spectra have redshift values lower than 0.07. Only as few as 46 spectra are of redshifts greater than 0.07. The redshift distribution of the ASA SNe (left plot) and spectra (right plot) is presented in Figure 2.1. As expected, the number of spectra peaks between 0 $\leq z < 0.01$.

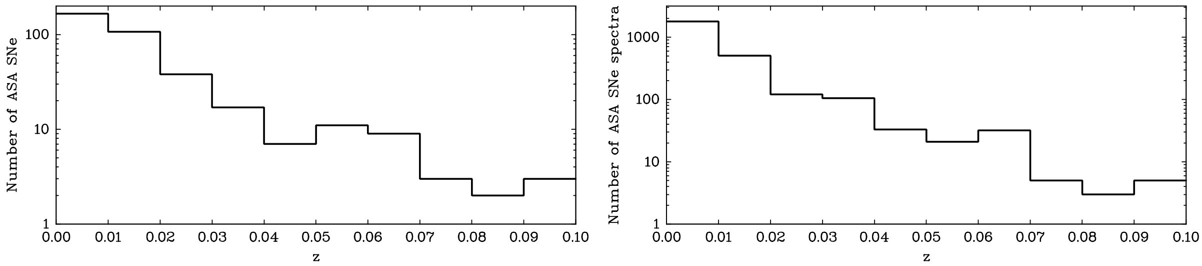


FIGURE 2.1– The redshift distribution of the ASA SNe and spectra for the $z \leq 0.1$.

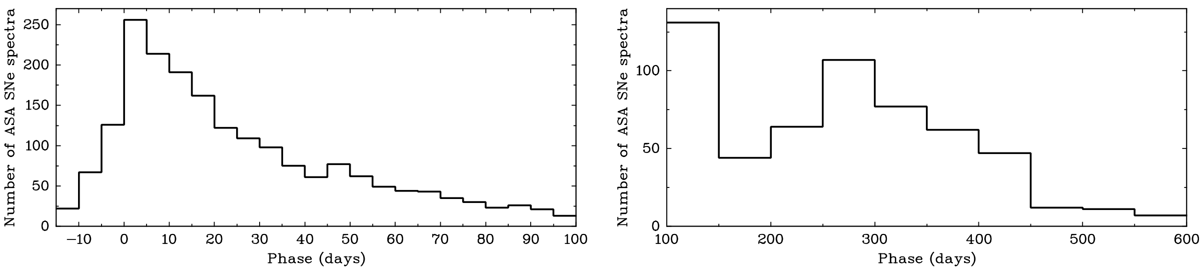


FIGURE 2.2– The phase distribution of the ASA SN spectra. Typically, the phases are relative to the B or R-maximum for type-Ia and type-Ib/c SNe and to the explosion epoch for SNe II.

The ASA spectra temporal coverage is good at all phases though, as one may expect, the number of the template spectra is greater near maximum light. Figure 2.2 shows the distribution of the spectra on the basis of their phase. The phases are relative to the B or R-maximum for type-Ia and type-Ib/c SNe and to the explosion epoch for SNe II. When these epochs are unknown, the phases relative to the discovery dates are used.

As an example of ASA data, in Figure 2.3 the spectra of type-Ic SN 2003jd are shown. The spectra are boxcar smoothed with a box size of 10Å. For each spectrum its phase relative to B maximum light is reported (from Valenti et al. 2007).

2.3 Archival software

In this section I describe the issues of the archive data homogenisation, addition and update. Taking in account the large amount of information to deal with, I developed automatic tools to carry out the above procedures.

The ASA contains only one-dimensional flux and wavelength calibrated spectra. The spectra are archived in FITS* format and are organised in folders (one folder per SN) where each spectrum represents one FITS file. The files are with the headers of their original raw FITS images (unless they have been

*Flexible Image Transport System - http://fits.gsfc.nasa.gov/

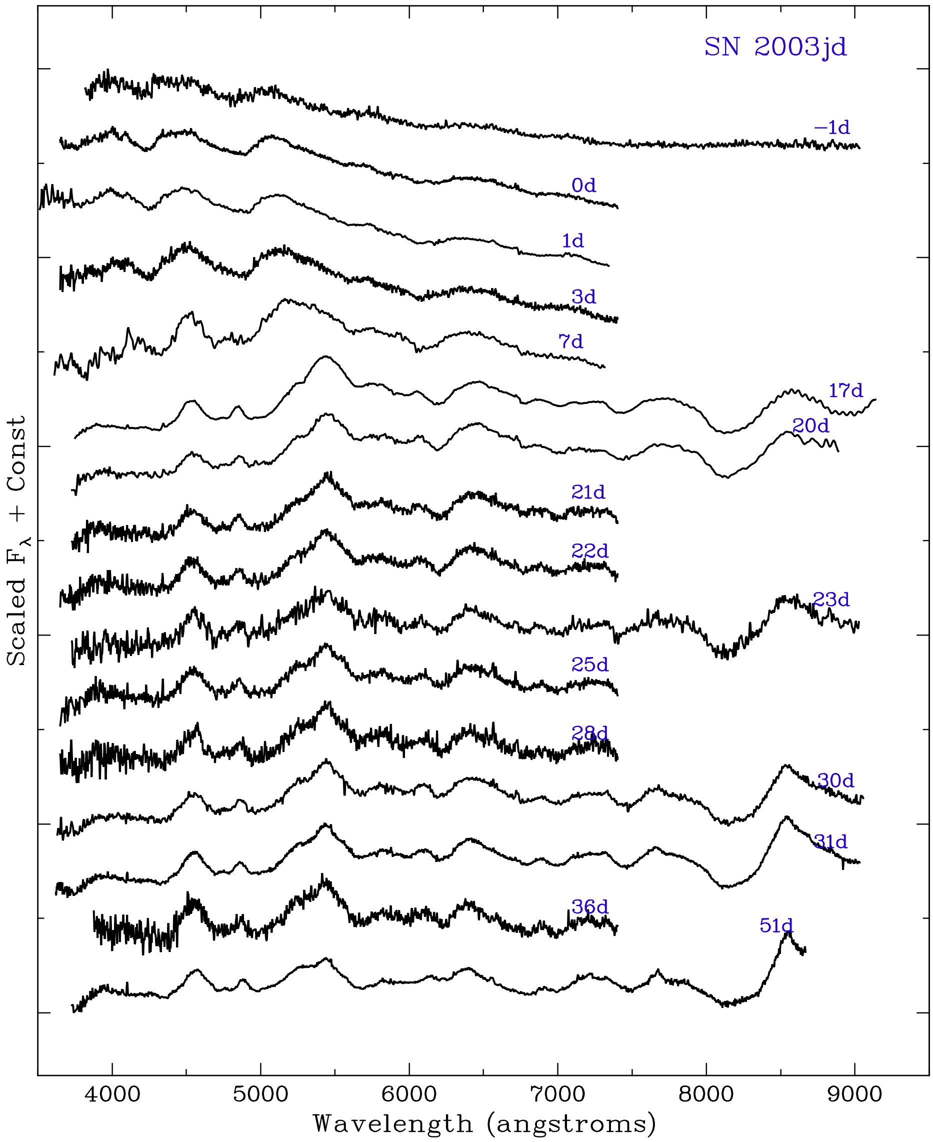


FIGURE 2.3– The ASA spectra of SN 2003jd (Valenti et al. 2007).

converted into FITS from other formats), thus essential information like the date and time of acquisition of the file or the telescopes/instruments used in observations may be retrieved from the header.

2.3.1 Homogenisation of the data

As a first step towards the organisation of the data, the group adopted a naming convention for the archive files. A common archive spectra file name is as follows: `<SN>_ <YYYY><MM><DD><Suffix>.fits`, where

- `SN` – the SN name, e.g. 2003cg,
- `YYYY MM DD` – the year, month and day of the observation, e.g. 20030423

- `Suffix` – a suffix (one character) added to the end of the file name in case a spectra of the same SN observed on the same date already exists in the archive.

Thus, `2003cg_ 20030423a.fits` file name means that it is the second spectrum (the first one is without any suffix) of SN 2003cg obtained on the 23-rd of April 2003.

Despite the FITS standard definitions, the format of FITS file headers varies on the basis of the system creating the files. In fact, each telescope/instrument data acquisition system creates FITS files headers in its own way. As already mentioned, the archive data have been (are) obtained during various observational programs performed at different sites, and the files coming from different sources have different set of header cards.

To homogenise and facilitate the access to certain set of information on a given spectrum new header cards with fixed format have been inserted in the header of every FITS file in the archive. This header card contains the essential information on the spectrum (e.g. SN name, the date of observation) and helps much the file information retrieval. The card with keyword `IDENT` was used for this. To conform the FITS specifications on the header, the card needs to have a predefined format: fixed length of keyword-value pairs, with the total length of 80 characters of the card. This implied certain rules on how the information is written in the card.

The format of the card is as follows:

`IDENT ="<JD> <SN> <Date> <Tel.>+<Instr.>+<Disp.> <Observ.>/<Reduc.> <Comm.>"` .

The meanings of the `IDENT` value elements and their formats are the followings:

- `JD` – the Julian Date (-2400000) of the observation, up to 8 characters, e.g. 52353.44
- `SN` – the SN name, up to 6 characters, e.g. 2002bo
- `Date` – the date of the observation, written in the YYYY-MM-DD format, 10 characters, e.g 2002-03-19
- `Tel.` – the telescope used, up to 7 characters, e.g. As1.82
- `Instr.` – the instrument used, up to 7 characters, e.g. AFOSC
- `Disp.` – the disperser used, up to 7 characters, e.g. gr4
- `Observ.` – the name (or initials) of the person who made the observation, up to 5 characters, ToO (Target of Oportunity)
- `Reduc.` – the name (or initials) of the person who reduced the spectrum, up to 5 characters, e.g. SB (Stefano Benetti)
- `Comm.` – comments, up to 6 characters, e.g. avg2 (average of two spectra).

Here is an actual `IDENT` card from a FITS file containing a spectrum of SN 2002bo observed on the 19-th of March 2002 in ToO mode at the Asiago 1.82m Ekar telescope, using AFOSC with the Grism 4:

`IDENT ="52353.44 2002bo 2002-03-19 As1.82+AFOSC+grn4 ToO/SB avg2"` .

Taking into account the above mentioned requirements on the format of information to be written in the header, it was obvious that an automatic tool was needed to write the data into a FITS file. Thus, I developed a tool to CHange or add the IDENT card to the header of a given FITS file (CHIDENT). CHIDENT prompts the user for necessary information to be added into the IDENT card. To facilitate this step CHIDENT controls the header for the presence of relevant information and displays it to the user in the course of the procedure. Then the tool verifies the information and formats it to fit the above mentioned criteria on the lengths of the data and, finally, it writes the new card in the header of the file. In case an old IDENT was already present in the header, is is replaced with the new one.

CHIDENT uses PyFITS* to read and update the headers. PyFITS module provides routines not only for the FITS headers, but also for the FITS data access and manipulation in the manner conforming the FITS standard. I largely used this module during the development of other software tools that will be described further.

2.3.2 Adding data to the archive

A significant attribute of the ASA is that it is continuously increasing by new inputs of fits files with spectra. The additions are made by the members of the group and to avoid eventual repetitions or errors a standard procedure of file additions (or updates) to the archive was needed. Besides, the archive is placed on one of our servers, while the final versions of reduced spectra to be added to the archive may reside on various user workstations. The above mentioned issues required a unique and secure mechanism of file transfers to the archive.

A tool uploading spectra FITS files to our archive was developed (SNUPLOAD). I further developed a Web based interface to give access to the tool through the standard Web browsers. SNUPLOAD is a server-side CGI (Common Gateway Interface) program which uses the HTTP protocol for receiving files from the clients (users).

SNUPLOAD works in the following way: it requests the user for the files to be added (up to 10 files). Then, it controls whether the specified are FITS files and also verifies whether they contain the IDENT card written in the appropriate format in their headers. After the successful verification the tool uploads the user files to the archive and changes the file names in agreement with the above mentioned naming conventions.

The upload program is a fast and secure way for sending the files to the archive from the users' workstations and in combination with CHIDENT it highly automates the process of the archive updates. I developed two other tools with Web interfaces to list and to delete the archive spectra for a specified SN. All these procedures proved to be useful tools for the archive files management and are widely used by our group members. The FITS file upload tool is accessible only in the observatory local area network (LAN).

As mentioned in Section 2.1, an important contribution to the ASA has been made by the European Supernova Collaboration (ESC). The observational data have been obtained by different nodes of the collaboration, we therefore needed to collect the spectra from the different participant institutions. Because of the above mentioned limitation of SNUPLOAD I have thus developed a new uploading tool

*a Python interface to FITS formatted files - http://www.stsci.edu/resources/software_hardware/pyfits

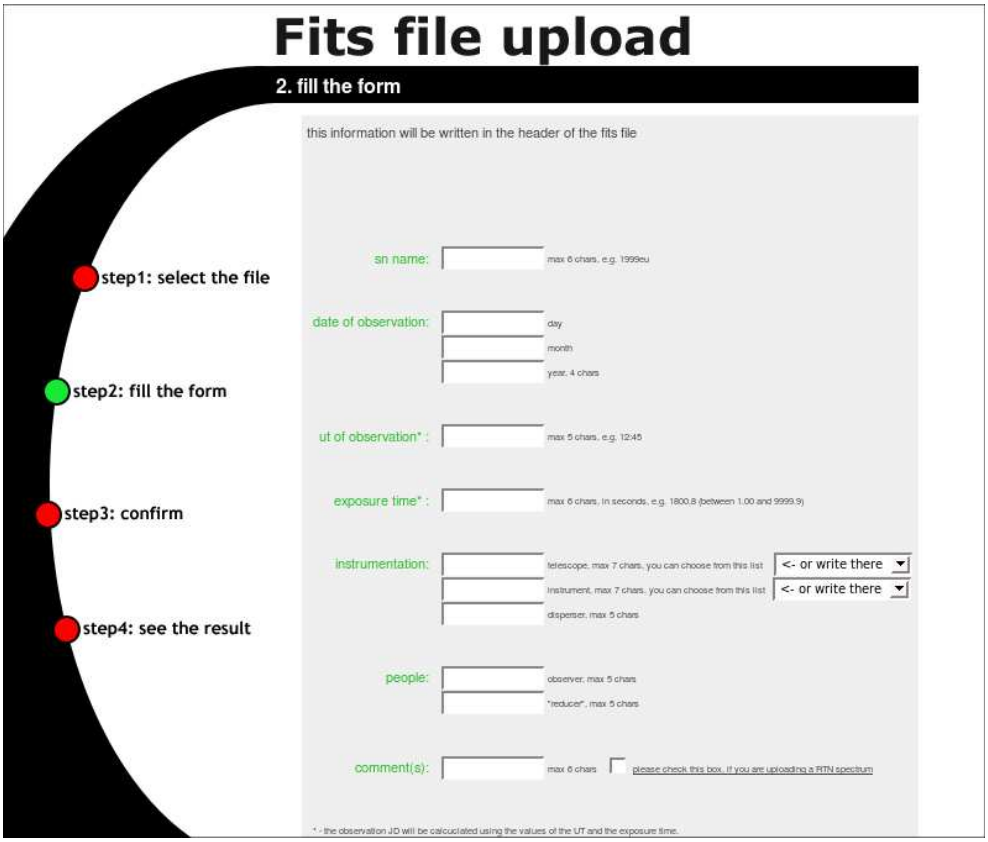


FIGURE 2.4– A screenshot of SNUPLOAD2 - the online upload tool. Step 2: the form to be filled by the user.

(SNUPLOAD2), satisfying the accessibility requirements.

As in the case of the LAN version of the tool, SNUPLOAD2 is a CGI program using HTTP for file transfers. I also designed a friendly web interface to make the process of data uploading more comfortable. The program is accessible via internet using the standard web browsers. Among the different characteristics of the software, I would like to emphasize the use of so called “cookies” for creation and control of sessions of client-server interaction. This feature is important from the process security and server performance points of view, but also for giving large flexibility to the program and making it more easy to use.

Since CHIDENT requires installation of the Python compiler and an additional external library, the distribution of CHIDENT is not a trivial task. Another approach was therefore used in the design of SNUPLOAD2. In contrary to the SNUPLOAD which requests user for a fits file with IDENT already inserted in the header, this tool requests users a real time compilation of an online form with the data necessary to create the IDENT card. This procedure must be repeated by the user for every upload and might become laborious in case many files were to be uploaded. However, I have made an effort to make the interface user friendly and self explanatory and taking in account that the number of files during an average upload session was around 10, the users did not report considerable inconvenients.

The followings are the steps the SNUPLOAD2 passes through: request for a file; file acquisition and analysis; request for the information; information acquisition and check; request for confirmation; file header modification and the file storage. After getting the file, the software verifies if it is a valid FITS file and then tries to extract the data of several relevant header cards. This is to give useful information to the user who is then going to fill and submit the form with the data that is used to compile the IDENT card. Before being inserted in the header these values are checked to conform with the ASA conventions for the card format. During the next step the user has a possibility to see the data and either to proceed with the last step of storage of the file in the archive or to cancel everything removing all the intermediate changes done. The program showed to be stable and fast, given the rather small dimensions of FITS files of spectra (∼30-40 KB on average). It takes small lapse of time to transfer tens of spectra.

The software tools described in this section were important instruments allowing us to homogenise and update the ASA. Thereafter, ASA is continuously increasing with new entries using the data collection tools.

2.4 The Asiago Supernova Catalogue (ASC)

The Asiago Supernova Catalogue has always been a major source of information for various studies performed by the group. Beside this, the automatic classification tools described in Chapter 4 make a wide use of the catalogue data. As already mentioned, the ASC too, can be considered an important part of the archive.

The ASC (see Barbon et al. 1989; 1999) contains data for all SNe discovered since 1885 and is the largest and most complete catalogue of this kind. Currently (October 2007), the ASC contains information of 4279 SNe. The catalogue is maintained by R. Barbon[*] and is publicly available on the Padova SN group home page[†].

The catalogue provides essential information of SNe and their host galaxies. For SNe, besides their equatorial coordinates and offsets from host galaxy nuclei, also the magnitudes, types and epochs of maximum (explosion) are listed. If available, the SN magnitudes at maximum, otherwise the discovery magnitudes are given. The SN types are obtained mostly from spectroscopy. If known, the epochs of maximum or explosion are reported, otherwise the date of discovery is listed. For the host galaxies the coordinates, morphological types, radial velocities and other photometric and geometric data are provided.

2.5 The Asiago LIght Curve Environment (ALICE)

The research of this thesis did not involve a wide use of the photometric data, but the Asiago LIght Curve Environment (ALICE) is an inseparable part of the SN archive and for the sake of completeness here I will present its brief overview.

Photometric data of 50 type-II SNe (see Patat et al. 1993; 1994) became the basis of the ALICE. Thereafter the archive have been enriched with data of SNe of all types and currently contains the broad band UBVRIJHK light and color curves for 283 SNe. For each object all photometric data have been collected in a single ASCII file, along with other information, such as the estimated epoch of maximum,

[*] roberto.barbon@unipd.it
[†] http://web.oapd.inaf.it/supern

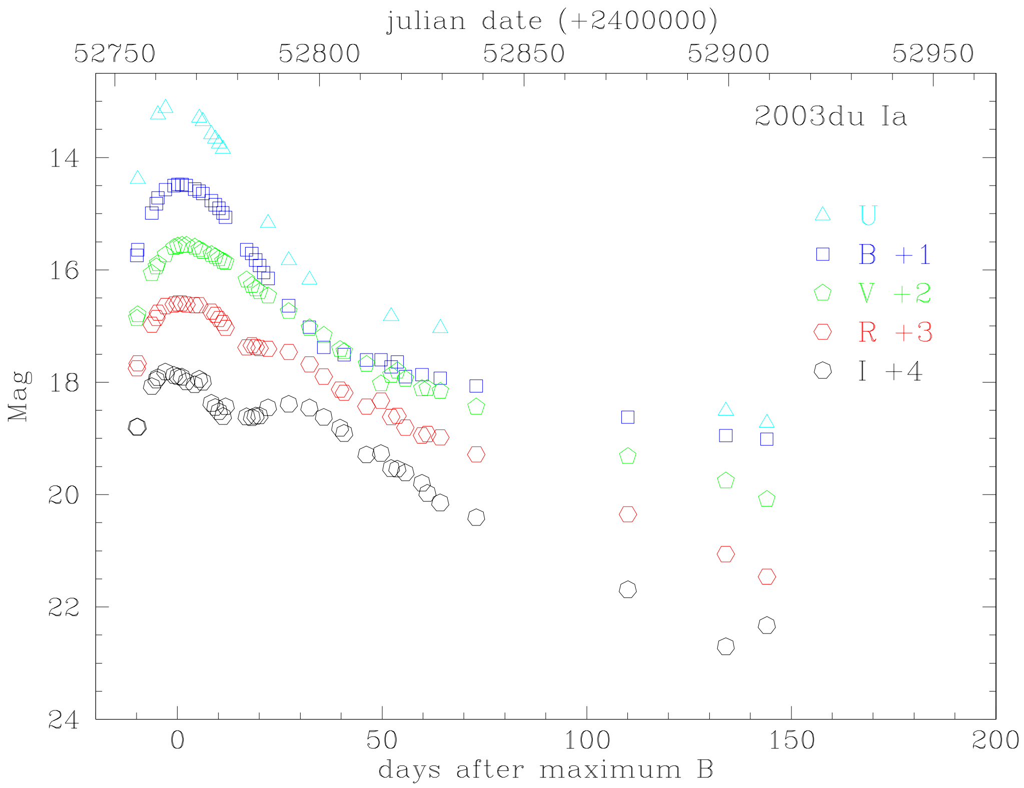


FIGURE 2.5– The ALICE UBVRI light curves of SN 2003du (see Stanishev et al. 2007).

the distance modulus of the parent galaxy and reddening. Simple software procedures have been developed to manage the data. The procedures allow, for instance, quick comparisons between the light curves of different objects or interactive least squares fits of single portions of the curves.

As an example of ALICE data, in Figure 2.5 the UBVRI light curves of type-Ia SN 2003du are shown (Stanishev et al. 2007).

2.6 Public SN spectra archives

The studies of large SN datasets are efficient ways of understanding of SN systematic properties. Thus, the availability of data collected by various SN groups to the community is an important issue. Though, at the moment the data of Padova - Asiago SN Archive are not directly accessible to the community, the Padova group has always been eager to share the archive material to the researchers. Also, almost all published ASA spectra have been made available to the community through SUSPECT*, an online database for the uniform collection, storage and dissemination of supernova spectra (Richardson et al. 2002).

SUSPECT contains over 1250 spectra of 144 SNe, a large fraction (probably more than half) of which are those from ASA, and is probably the largest public SN spectra archive. It collects also photometry

*http://bruford.nhn.ou.edu/∼suspect

from observers and provides a variety of ways to search for the data. In the near future the SUSPECT plans to include supernova polarization spectra and GRB optical afterglow photometry. Another archive worth to mention is the CfA SN archive*, that has more than 350 publicly-available spectra of 20 SNe, The archive contains also photometric data.

Though the ASA spectra are becoming public via continuous contributions to SUSPECT, we plan to develop and maintain our own online spectra database.

*http://www.cfa.harvard.edu/supernova/SNarchive.html

3

Supernova Spectra Comparison Tool

WITH THE MOTIVATION (see Chapter 1) to achieve an automatic objective classification of SNe, in the Padova SN group we developed a tool that compares a spectrum (input spectrum)with the set of SN spectra from ASA (see Chapter 2).

In this chapter I present the PAdova Supernova Spectra comPARison TOOl (PASSPARTOO), a collection of software procedures performing the automatic comparison of SN spectra. The first version of the program was presented in Harutyunyan et al. (2005). Designed for different purposes and working with slightly different algorithms, all the procedures carry out an automatic comparison of an input spectrum with a set of well-studied SN spectra (templates), in order to find the template spectrum that is most similar to the given one.

Among these procedures, the most used one is the GEneric cLAssification TOol (GELATO), which is optimised for objective classification of SN spectra. Thus, the Section 3.1 is focused on GELATO with a detailed description of the algorithm. Further, I describe two other spectra comparison routines of the PASSPARTOO collection, showing different approaches. The last section of the chapter is devoted to a short discussion of SN spectra comparison tools developed by other groups and to discussions for future improvements of the software.

3.1 GEneric cLAssification TOol (GELATO)*

3.1.1 The approach

A few groups have developed software tools (see Blondin & Tonry 2007; for a discussion) for SN spectra analysis that, using different technical approaches from χ^2 minimisation to cross-correlation, aim to different immediate results like SN classification or quantification of spectral differences.

Our goal in the design of the software classification tool (GELATO) was to replicate as much as possible the outcome of the detailed comparison by an expert SN observer who, given an indefinite amount of time, performs a detailed comparison of a given input spectrum to a large number of archive

*some material from this chapter will be published in A&A

TABLE 3.1– GELATO bins with wavelength ranges and SN spectra principal features entering the bins.

Bins	Wavelength range	SN spectra features		
	Å	Ia	Ib/c	II
1	3504 - 3792	Ca II	Ca II	Ca II
2	3800 - 4192	Si II, Ca II	Ca II	Ca II, H_δ
3	4200 - 4576	Mg II, Fe II	Fe II	Mg II, Fe II, H_γ
4	4584 - 4936	Fe II	Fe II	Fe II, H_β
5	4944 - 5192	Fe II	Fe II	Fe II
6	5200 - 5592	S II	S II, OI	S II
7	5600 - 5896	Si II, Na I	Na I, He I	Si II, Na I
8	5904 - 6296	Si II	He I	Si II
9	6304 - 6800	Fe II	Si II, He I	O I, H_α
10	6808 - 7904	O I	O I	O I
11	7912 - 9000	Ca II	Ca II	Ca II

spectra. The aim of our software is to save human-expert time, make the process repeatable and give a guide for non-experts.

In GELATO development I used the approach discussed in Riess et al. (1997) and Rizzi (1998). The tool divides the input spectrum and all template spectra in a number of spectral bins. The comparison of spectra is done in each bin (∼250-1100Å wide), so that the distortion of the SED caused by the reddening is reduced compared with the entire spectrum. Thus, such approach for spectra comparison has the advantage of minimising the effects of reddening in SN spectra, giving priority to the presence and strength of the spectral features.

The bins are selected to contain the spectral features most significant for SN classification and dating. The wavelength range for the selected bins and corresponding principal spectral features of the main SN types are listed in Table 3.1, while Figure 3.1 identifies the boundaries of the GELATO spectral bins overplotted in SN spectra.

A unique set of fixed bins is adopted for comparison of spectra of all SN types. The performance of the tool and classification results with this set of bins have been found satisfactory (see Chapter 4), though we are considering variable bins as an improvement for a new version of GELATO.

3.1.2 The templates pre-processing

All the spectra from ASA have been inspected to select the templates for the comparison procedure. See Chapter 2 for an overview of ASA (template) spectra, their number and their type, phase and redshift distributions.

The comparison procedure is rather simple, however certain processing of spectra is needed before the comparison. In the first version of the comparison tool these manipulations were done “on the fly”, i.e. at the moment of the comparison, when the program was launched. Taking in account the large

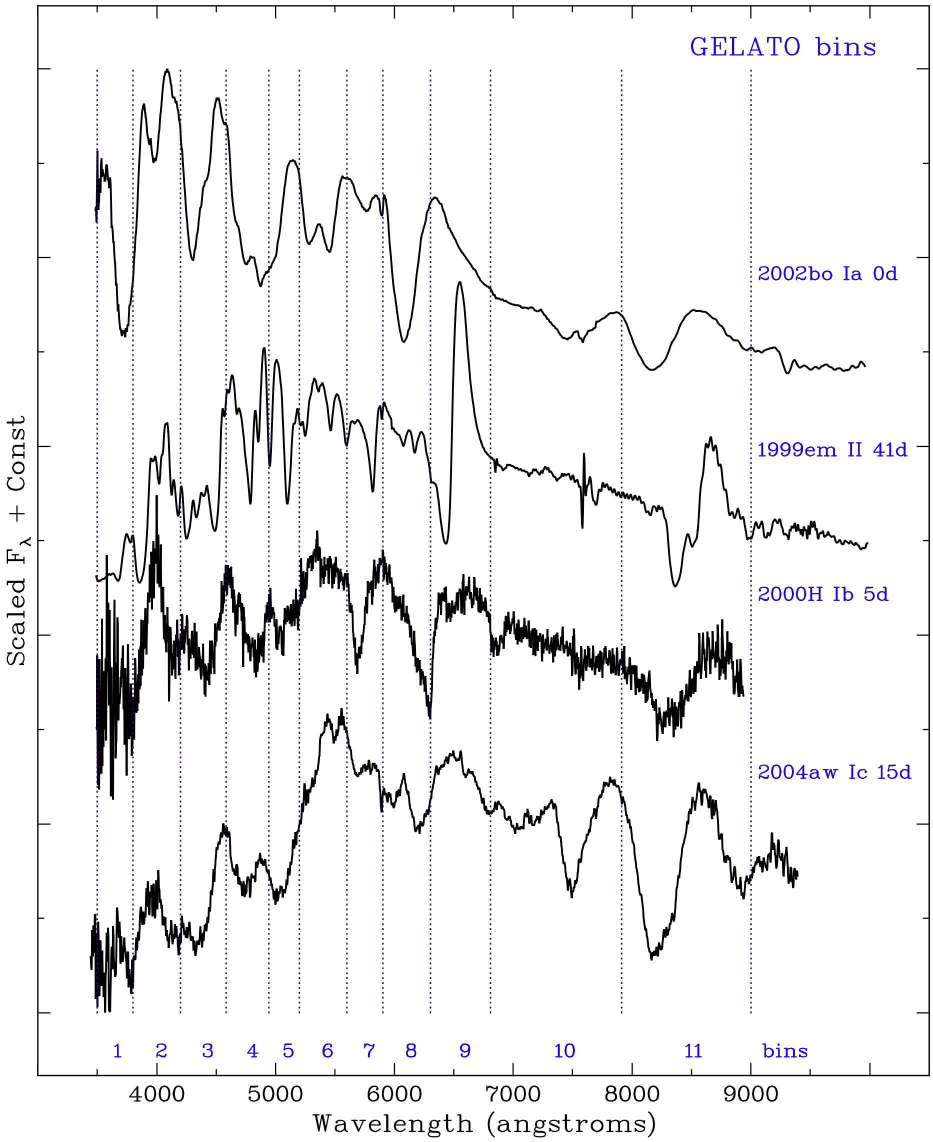


FIGURE 3.1– The GELATO bins. The dotted lines are the bin boundaries overplotted on the spectra of SNe of different types. The spectra are in the parent galaxy restframe.

number of template spectra, this approach caused the program to run for a considerable amount of time (about 12-15 minutes, depending on the machine load, on one of our fast machines). To overcome such an inconvenient, the new version of the tool was designed to use a set of pre-processed templates, ready for comparison. In this section I describe the template spectra pre-processing.

The Asiago SN Catalogue (ASC, Chapter 2) is widely used during the pre-processing of the template spectra. Essential information like types, redshifts and maximum (or explosion) epochs of template SNe are obtained from the ASC. A MySQL* database, containing the ASC data, is maintained to automate

*http://www.mysql.com/

the process of the information retrieval.

The pre-processing of template spectra consists of the following steps:

✔ **redshift correction** – the template spectra are reported to galaxy restframe. The radial velocities of respective objects are obtained from the ASC.

✔ **boxcar smoothing** – To reduce the noise a boxcar smoothing is performed on the spectra. For the smoothing, a box size corresponding to ∼70Å is adopted. This smoothing is sufficient to remove high-frequency noise components from the spectra and at the same time preserves the spectral features. In fact, a typical SN spectral feature is from several hundreds to several thousands angstroms wide and is not significantly affected after 70Å boxcar smoothing. A special case are SNe IIn, that can have spectral features as narrow as ∼40Å. These narrow features are caused by the CSM-ejecta interaction and are not intrinsic to the SNe, thus, in general, they carry less information on the SN. However, these cases are treated separately and a box size as small as ∼30Å is used then. In the new version of GELATO the box size will become a parameter accessible to the user. Figure 3.2

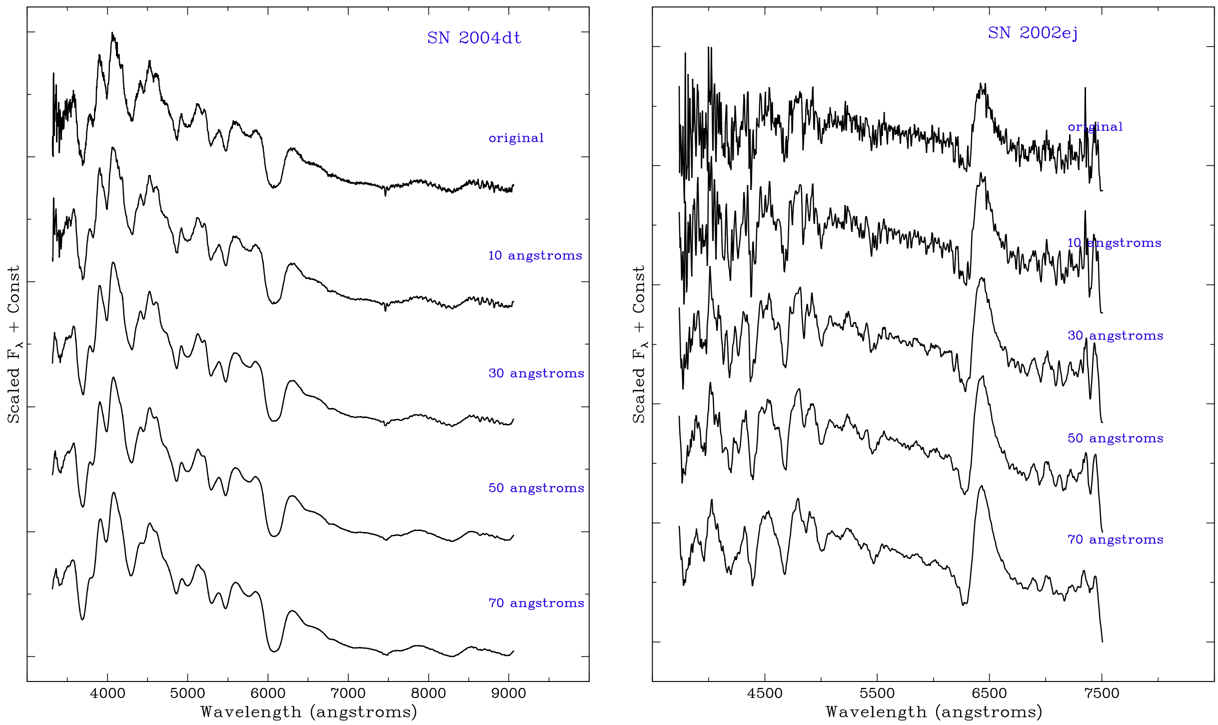


FIGURE 3.2– The original and smoothed spectra of type-Ia SN 2004dt (Altavilla et al. 2007) and type-II SN 2002ej (Section 4.1). The spectra are in the parent galaxy restframe. The numbers near the smoothed spectra are the corresponding box sizes.

shows results of smoothing performed with various box sizes. The original and smoothed spectra of type-Ia SN 2004dt (Altavilla et al. 2007) and type-II SN 2002ej (Section 4.1) are displayed, and the different box sizes used for smoothing are reported. A similar smoothing performed on the type-IIn SN 2003G spectrum (ASA) shows that the Hα emission narrow component is severely reduced when 70Å-wide box is used (Figure 3.3).

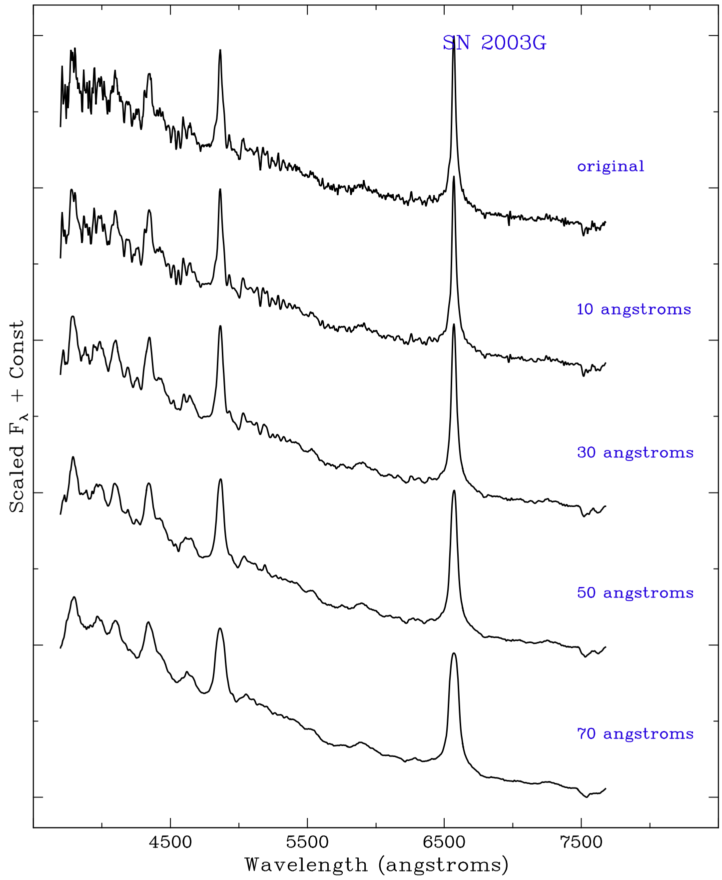


FIGURE 3.3– The original and smoothed spectra of type-IIn SN 2003G (ASA). The spectra are in the parent galaxy restframe. The numbers near the smoothed spectra are the corresponding box sizes.

✔ **resampling** – After smoothing, the spectra are resampled, so the number of the data points is the same for all the spectra. The resampling is done using linear interpolation with a fixed step of 8Å. In the current version of GELATO the resampling step is constant. As the smoothing box size, the variable resampling step will be implemented in the new version of GELATO and will become a user-accessible parameter.

✔ **division in bins** – The final step of the template processing is the division in bins. The bins are those presented in Table 3.1 and Figure 3.1. At the extremes a spectrum may not cover the entire length of a bin, thus the first and the last bins at the spectrum ends may not be entirely sampled. In any case, the comparison in these bins is done in the overlapping region of the input and the template spectra.

After all the above mentioned manipulations are performed, the templates are ready for comparison. For every spectrum the pre-processing software creates a single file that contains all redshift-corrected, smoothed and resampled bins.

3.1.3 Determining the best matching template

When GELATO is launched, it manipulates the input spectrum in the same way as the templates. The only parameter the user is requested for, is the redshift of the input spectrum. After processing the input spectrum and loading the pre-processed templates, the GELATO code proceeds as follows: for each of the N bins of the input spectrum it computes δ_j, the mean relative distance between the j-th bin of the input spectrum and the corresponding normalised bin of the template. This operation is iterated through all the template spectra and the average of the δ_j values for each template spectrum is calculated. If f_i is the input spectrum at wavelength λ_i (in the j-th bin) and F_i is the template, we define δ_j as follows:

$$\delta_j = \frac{1}{n \cdot < f >_j} \sum_{i=1}^{n} | f_i - F_i^{norm} |, \tag{3.1}$$

where F_i^{norm} is the F_i flux scaled to the input spectrum flux within the j-th bin, n is the number of spectral elements and $< f >_j$ is the mean value of the flux in the j-th bin.

$$\Delta = \frac{1}{N} \sum_{j=1}^{N} \delta_j, \tag{3.2}$$

where N is the number of bins. The most similar template is the one that minimises the value of Δ.

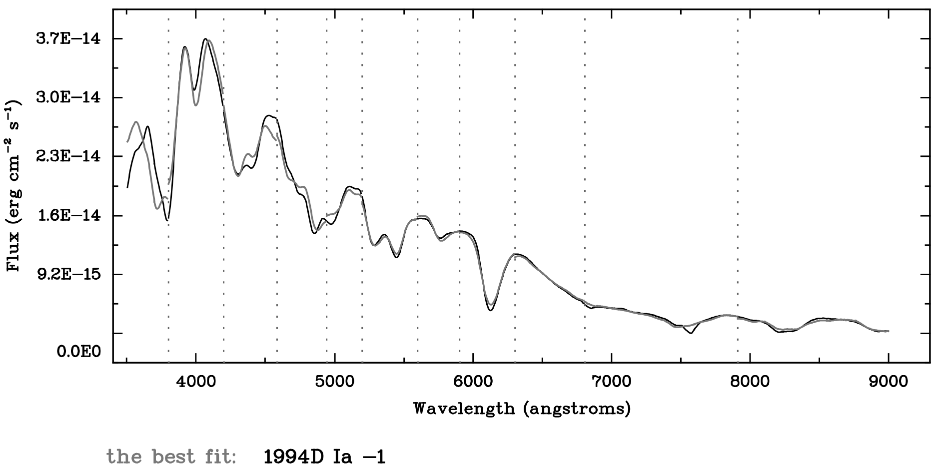


FIGURE 3.4– The output of GELATO for the comparison of the SN 1996X 0 day spectrum (top panel) with its best matching template, the SN 1994D -1 day spectrum. The black line is the input spectrum, while the gray one is the template, divided in the bins. Every bin is scaled in flux to match the corresponding bin of the input spectrum. The dotted lines are the bin boundaries. See Figure 3.5 for the original spectra.

As an example, using GELATO we compared the type-Ia SN 1996X maximum light epoch spectrum (Salvo et al. 2001) with our template spectra. For this comparison we excluded all the spectra of SN 1996X from the template database. The best fitting template found by the tool is the type-Ia SN 1994D -1 day spectrum (Patat et al. 1996). Figure 3.4 displays the graphical output of GELATO. In the plot the black line is the (input) spectrum of SN 1996X, while the gray line is the best fitting template (SN

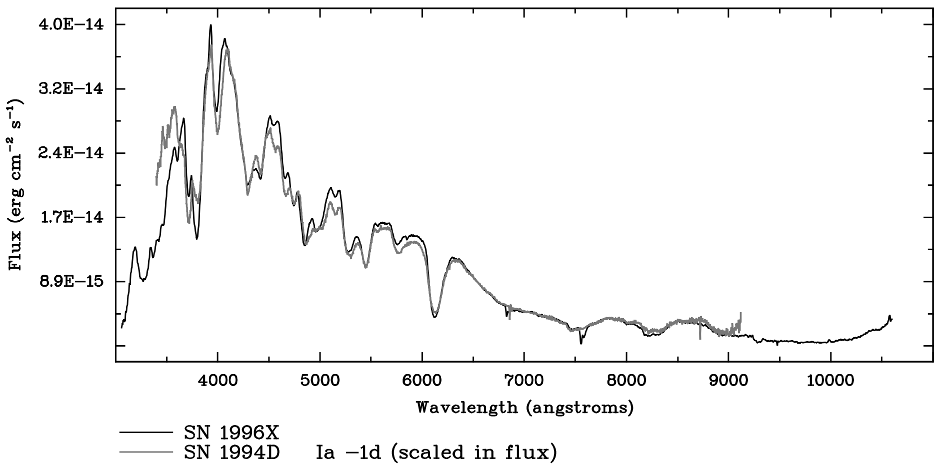


FIGURE 3.5– The overplot of the original of the same SN 1996X 0 day spectrum with the original spectrum of SN 1994D at -1 day (see Figure 3.4 for the GELATO output of this case). The black line is the input spectrum, while the gray one is the template. The spectra are not corrected for reddening and are in the parent galaxy restframe.

1994D) spectrum, divided in bins. Every bin is scaled in flux to match the corresponding bin of the input spectrum. The dotted lines are the bin boundaries. Figure 3.5 shows the overplot of the original spectra.

Because of the division in spectral bins and the fact, that single bins are treated independently, the comparison procedure depends little on the slope of the continuum (hence, reddening) and gives priority to the presence and strength of spectral features. This can be seen, for example, when we compare the spectrum of type-Ia SN 2002bo at -1 day (Benetti et al. 2004b) with our template database (excluding the SN 2002bo spectra). The top panel of Figure 3.6 shows the output of GELATO with the best match template (SN 1999dk -2 days, ASA), while the original spectra are displayed in the right panel. Despite the difference in SED, the program is able to find the template that best fits the spectral features of the input.

3.1.4 The goodness-of-fits and SN classification

The software achieves the goal of finding the best fitting archive spectrum to a given input spectrum, through the minimisation of Δ values. However, Δ alone does not describe the quality of the fit, which is necessary for a quantitative comparison. Thus, we tried to obtain a quantitative measurement of goodness-of-fit.

As also mentioned before, because of reddening or errors in flux calibration the continuum shape of SN spectra can often be misleading to show the similarity of two spectra. We adopted the approach of the bin division, trying to discard as much as possible the SED information. However, we are less confident in finding the degree of similarity for a spectrum with weak lines and dominating continuum, than for a spectrum with pronounced, strong features. In other words, one can evaluate better the similarity between spectra in the presence of spectral lines. Thus, the classifications of spectra are safer when they contain strong features.

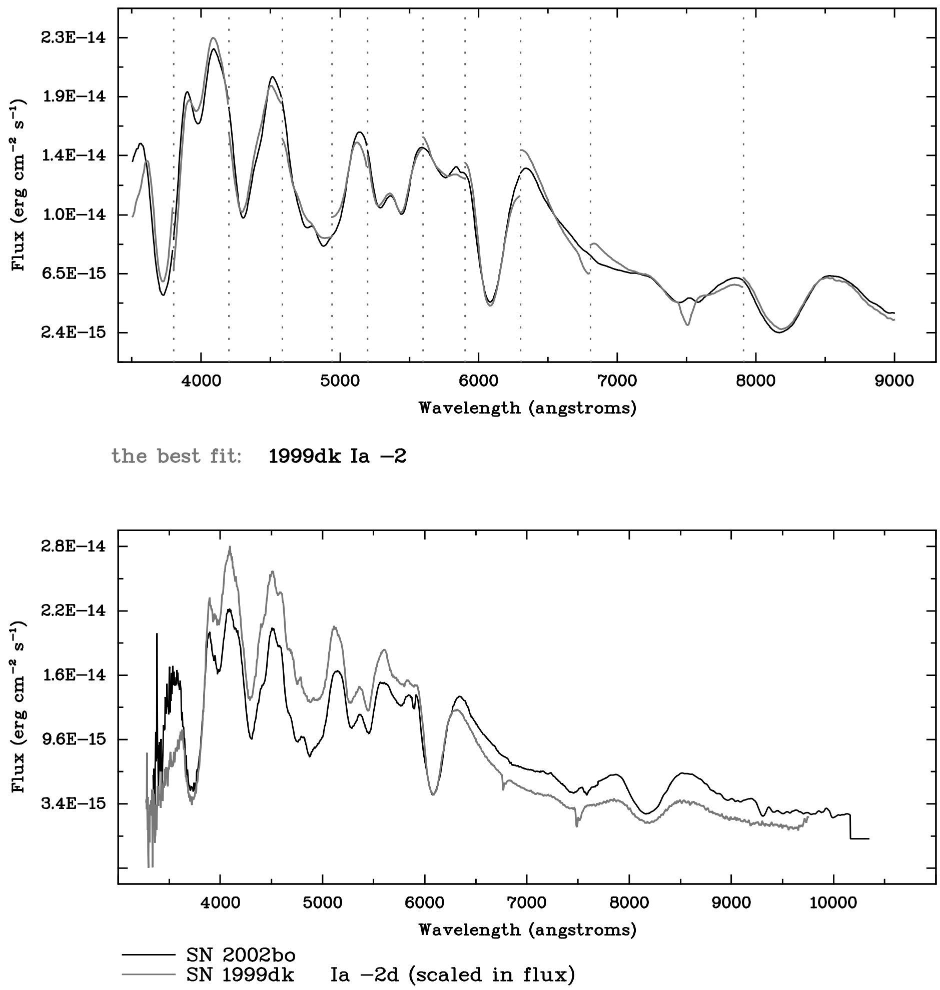


FIGURE 3.6– The type-Ia SN 2002bo -1 day spectrum with its best match SN 1999dk at -2 days. Despite the difference in the SED, the best fit found by GELATO resembles all main spectral features of the input. The spectra are in the parent galaxy restframe and not corrected for the reddening.

In general, we noted that the values of Δ computed by the software for the cases of spectra with dominating continuum and weak spectral features are systematically lower than those of spectra that have many strong spectral features. To account for this, we calibrate the Δ values using coefficients that indicate whether the spectra are more or less feature-rich. We defined a so called feature-richness-parameter (FP) as follows:

$$FP = \frac{1}{N}\sum_{j=1}^{N}\frac{1}{n}\sum_{i=1}^{n}\frac{|f_i - F_i^{flat}|}{< f >_j}, \tag{3.3}$$

where F_i^{flat} is the best fitting straight line to the spectrum in the given bin.

Figure 3.7 (lower panel) shows the 61 day spectrum of type-II SN 1995ad (Pastorello 2003), divided in bins together with corresponding best fitting straight lines (F^{flat}). In the upper panel of the figure,

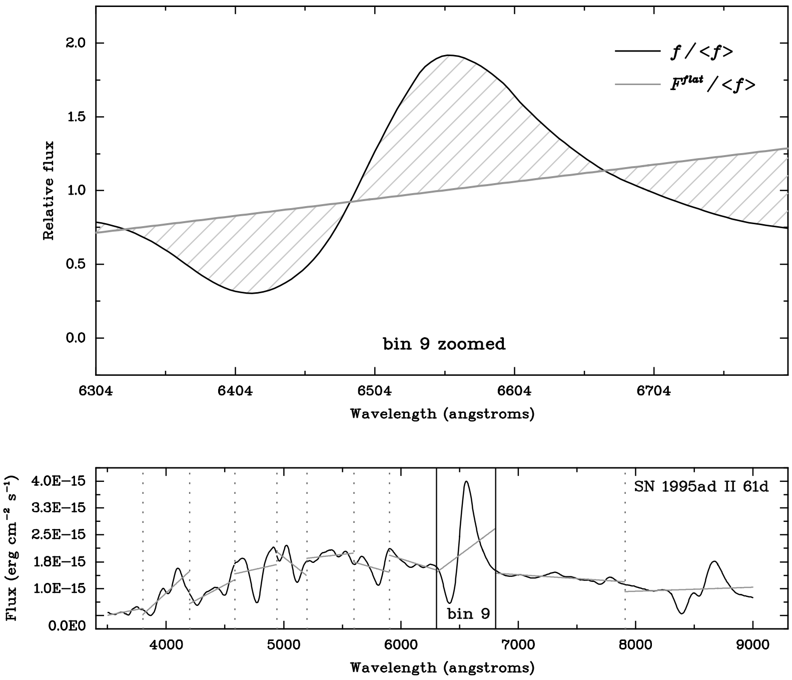


FIGURE 3.7– In the lower panel the 61 day spectrum of type-II SN 1995ad (Pastorello 2003) is displayed with corresponding best fitting straight lines (F^{flat}-s). The upper panel shows the zoom of bin 9 of the spectrum normalised to its mean value ($f \,/ < f >$) together with the normalised straight line ($F^{flat} \,/ < f >$). The shaded area is then $|f - F^{flat}| \,/ < f >$.

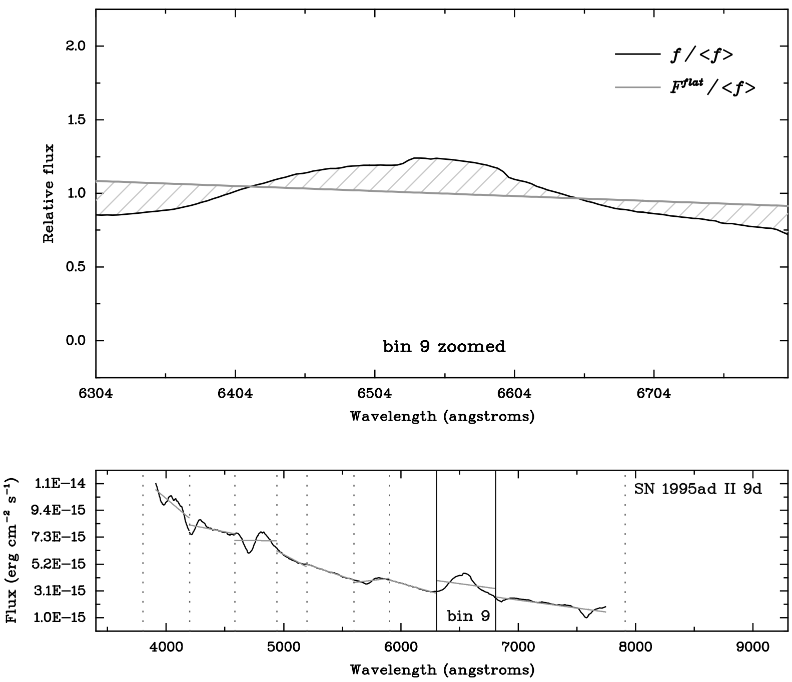


FIGURE 3.8– The same as Figure 3.7, but for the 9 day spectrum of type-II SN 1995ad (Pastorello 2003).

for one of the bins (9-th) the spectrum normalised to its mean value ($f \ / < f >$) is zoomed. The gray straight line in the upper panel is $F^{flat} \ / < f >$, thus the shaded area represents $|f - F^{flat}| \ / < f >$.

For each fit of spectra we then define the goodness-of-fit (*GoF*) value by the following expression:

$$GoF = \left(\frac{\Delta}{FP}\right)^{-1}. \tag{3.4}$$

The graphical representation above (Figure 3.7) helps to emphasize the meaning of FP and GoF. Δ and FP are defined in an analogous manner: FP is the Δ measure for the input spectrum compared with s piecewise straight lines, fitting the spectrum in each bin. Then, $GoF = 1$ means that the template fits the input no better than a piecewise linear function. In the example shown above the $FP = 0.38$ for the zoomed bin, and 0.23 for the entire spectrum. For comparison, the plot for the spectrum of type-II SN 1995ad 9 days after explosion (Pastorello 2003) is shown in Figure 3.8. In this case the features are weaker and in general the spectrum is not as "feature-full" as the previous example. The corresponding FP for the 9-th bin is equal to 0.13 and the one for entire spectrum to 0.07.

The *GoF* allows a numerical estimate of the quality of the fit, which can be used to compare the fits of different SN. As an example, in Figure 3.9 the graphical outputs of GELATO for the spectra of SN 2002an and 2005bs are presented. In the figures the smoothed versions of the input spectra (black lines) and best fitting templates (gray lines) together with bin boundaries (dotted lines) are displayed. See Section 4.1 for a discussion and plots of the original spectra.

The Δ value of the fit in the SN 2002an case is smaller than that of the SN 2005bs case ($\sim$0.02 and 0.07, respectively), but SN 2005bs is more feature-rich than SN 2002an. The resulting GoF is greater for SN 2005bs ($\sim$3.3) than for SN 2002an ($\sim$1.7), hence the former should be regarded as a better fit than the latter. Such a definition of the *GoF* allows us to somehow replicate the expert astronomer evaluation in the SN spectra comparison.

I tested the *GoF* values comparing spectra to different sets of templates. In addition, the outputs of GELATO has been compared to the independent classifications by three expert astronomers. The results combined with visual inspections of the fits showed that GoF $\geq$ 1.4 means a high / satisfactory quality of the fit and safe SN type determination, while GoF $<$ 1 occurs when the input is a peculiar SN with no actual match in the archive. Intermediate values $1 \leq$ GoF $<$ 1.4 may result either for fair/good fits with correct type detection or poor fits with incorrect type detection. While further tests will be needed to refine the goodness-of-fit estimation and establish the confidence levels on the basis of the goodness-of-fit values, no inconsistency has been detected in GELATO results so far. The current version of GELATO is routinely used by the members of the Padova SN team for the classification of newly discovered SNe and shows coherent and fair performance.

3.2 SN age determination using GELATO

As already mentioned, the SN spectra evolve with phase, thus, ideally, from a single SN spectrum it should be possible to determine the phase of the object. In practice, this works rather well for type-Ia SN, since they are a homogeneous group of objects which, in particular, near maximum light show considerable evolution (both in luminosity and spectra) on a daily basis. In fact, several works dedicated

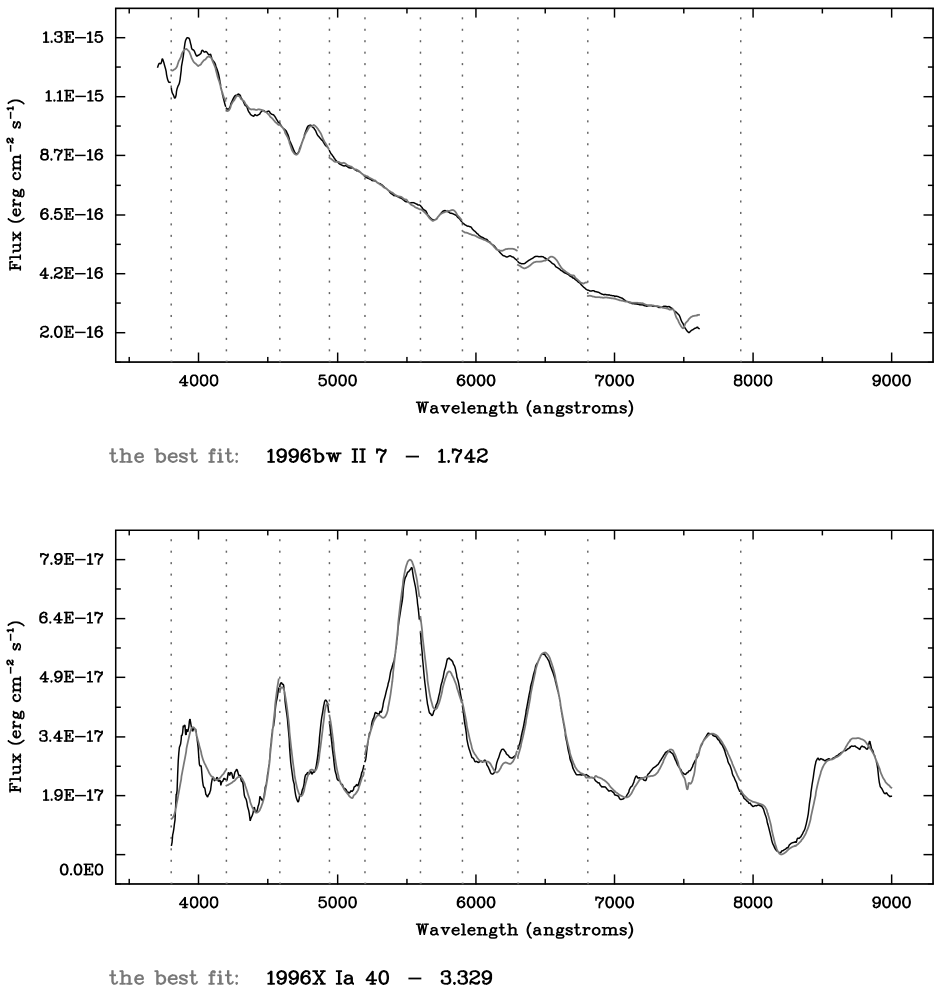


FIGURE 3.9– The graphical output of GELATO for the spectra of SN 2002an (top panel) and SN 2005bs (bottom panel). The spectra are in the parent galaxy rest frame. The black lines are the input spectra and the gray ones the best fitting template spectra, divided in bins and scaled in flux to match the input spectra in the respective bins. See Section 4.1 for a discussion and plots of the original spectra.

to the type-Ia SN phase determination using spectra (Riess et al. 1997; Rizzi 1998; Blondin & Tonry 2007) have shown that the precision in the age estimates can be as good as ∼2-3 days when compared in the photospheric phase.

The situation is different with CC SNe. The large intrinsic differences in their physical properties result in a large variety of their display. In addition, the imprecision of the explosion epoch determination for SNe II introduces a large error in the phase estimates. Also, type-IIP SNe in the plateau phase (spanning for 2-3 months) vary very little, showing almost constant spectra. For type-Ib/c SNe, instead, only few template spectra with good temporal coverage are available.

To check the ability of GELATO, in combination with ASA, to determine the SN spectral age, we carried out several tests for various SN types. For SNe Ia, as test cases I used the spectra of a set of well-studied events observed by the ESC (Section 2.1). The spectra were those of SNe 2002bo (Benetti

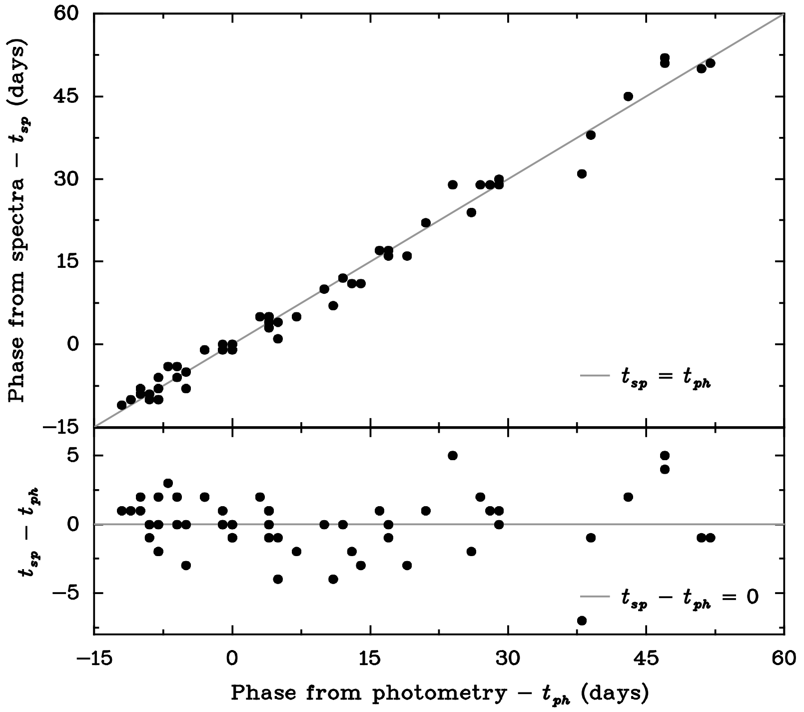


FIGURE 3.10– The phases from spectroscopy compared to the phases from photometry for the sample of type-Ia SNe.

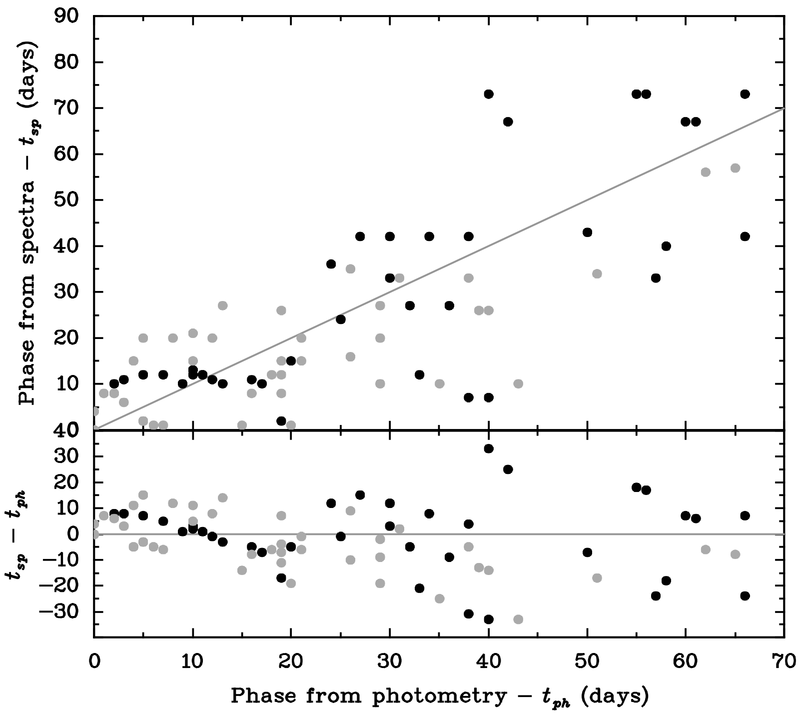


FIGURE 3.11– The same as the previous figure, but for type-II (black dots) and type-Ib/c (gray dots) SNe.

et al. 2004b), 2003cg (Elias-Rosa et al. 2006b), 2003du (Stanishev et al. 2007), 2004dt (Altavilla et al. 2007), 2004eo (Pastorello et al. 2007a), 2005cf (Garavini et al. 2007), for which detailed light curves are also available.

Each spectrum of these objects was compared with those of a sample of a dozen template SNe Ia, which included objects spanning the entire range of SN Ia properties (e.g. SN 1991bg and 1991T). Then, we compared the phases of the best fitting template spectra obtained from the spectral comparison with the phases derived from photometry. The results are plotted in Figure 3.10. The plot shows that the two phases are in a good agreement. The difference of the phases shows a RMS of about 3.1 days in the phase range from 15 to 60 days, while in the range -15 to 15 days it is as small as 1.9 days. The increase of the error with age is expected, because the evolution of type-Ia SNe slows down as their age advances.

Similar tests done with a set of type-II and type-Ib/c revealed, as expected, larger errors: RMS $\sim$ 14 days for SNe II and 11 days for Ib/c (see Figure 3.11). As already said, the errors are larger compared to that for type-Ia SNe due to the heterogeneous behaviour of SNe II and Ib/c and for type-II SNe, even to the fact that the explosion epoch is often poorly known.

3.3 Other comparison tools of PASSPARTOO collection

GELATO is the most widely used tool of PASSPARTOO collection, however, during its development a couple of other spectra comparison procedures have been designed too. Despite the relatively smaller amount of time, dedicated to the refinement and testing of these procedures, they showed to be particularly useful for special purposes and hence worth to be mentioned.

3.3.1 Independent spectral bins comparison tool

This procedure compares the spectra divided in bins and from this point of view it is similar to GELATO. In fact, the spectral intervals in which the spectra are divided before the comparison are identical to those of GELATO (see Section 3.1, in particular Table 3.1 and Figure 3.1). Different from GELATO, the division is followed by the independent comparison of each interval of input spectrum with the corresponding one of the template spectra. As a result, for each input spectrum bin independently, the tool reports the best matching template bin.

This means that for an input spectrum with a complete spectral coverage (to have the entire set of 11 bins in input), eleven best fitting template spectra will be found, and the output of the tool is not a single best match SN, but a list of SN that match the input each in a given spectral range. The resulting eleven "best match" SNe can in principle led to a classification and possibly to a phase determination of the input spectrum, especially if the same template SN matches most of the bins. This tool is more useful to search for similarities of single spectral features in different SNe. The best fitting templates determination is done, as for GELATO, calculating the mean relative differences of the bins and minimising them.

In Figure 3.12 the comparison of the type-Ia SN 2002bo spectrum 28 day after B-maximum (Benetti et al. 2004b) performed by the procedure is displayed. The best-match templates are scaled in flux to match the input spectrum flux in the corresponding bin. The output shows that the best-match objects have very similar spectral features as for the expansion velocity and lines. In addition, the input spectrum can be unambiguously interpreted as that of a type-Ia SN about one month after maximum.

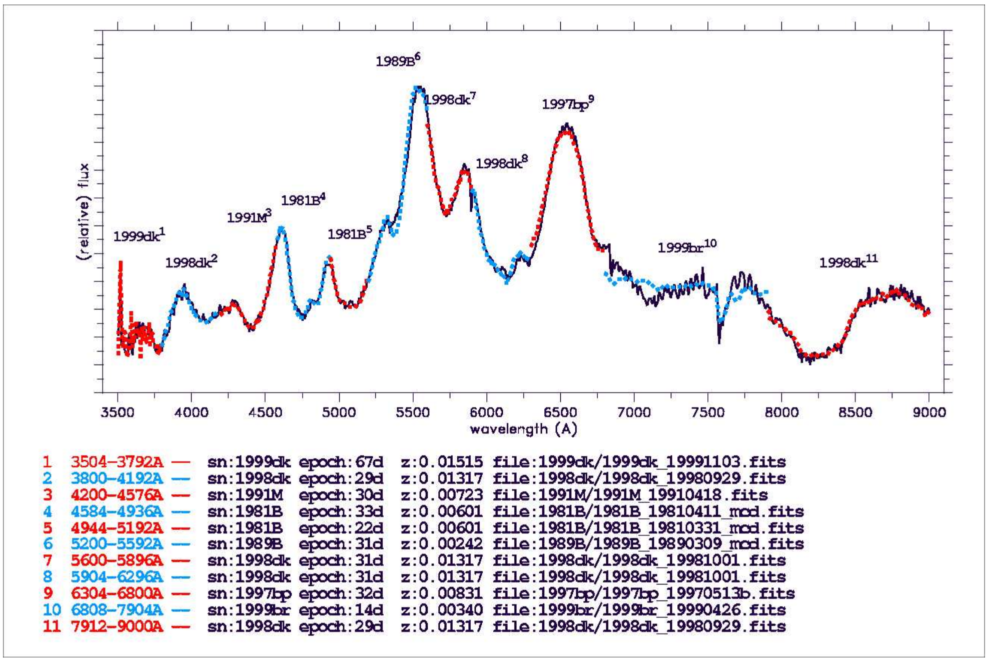


FIGURE 3.12– The comparison of the type-Ia SN 2002bo spectrum 28 day after B-maximum with the templates. The input spectrum (black line) is overplotted with the best match for every bin (dotted lines). Below the best match SNe with their redshifts and phases are reported. The output shows that the best match objects have very similar spectral features with the same velocity and relative shape. In addition from this result the SN in input can be unambiguously interpreted as a type-Ia SN about one month after maximum.

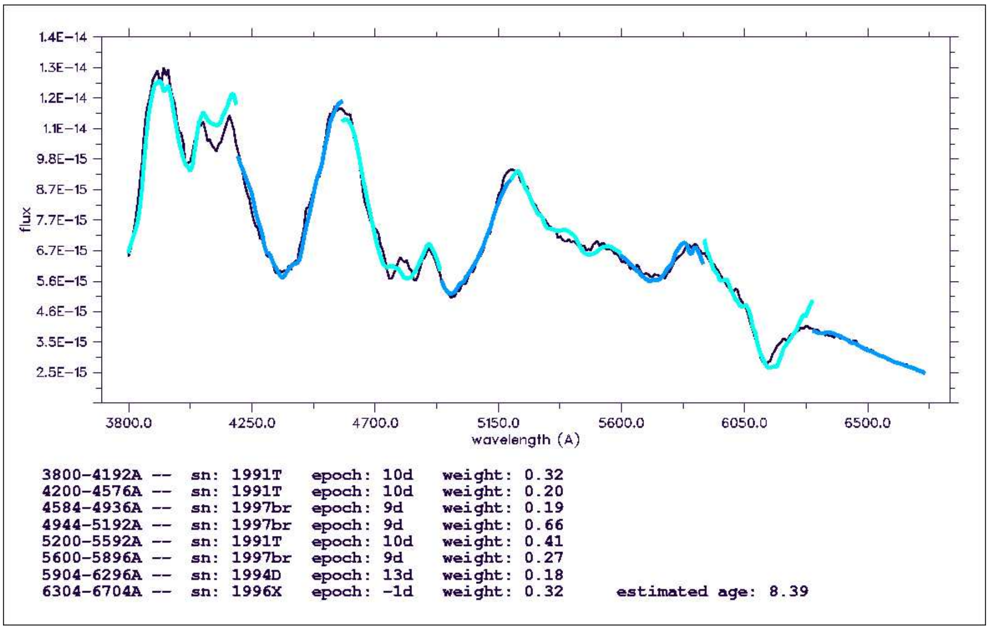


FIGURE 3.13– In order to estimate the age of the SN 1999cw spectrum, the program calculates the weighted mean of the ages of the best match template spectra for different parts of the spectrum. The weights assigned to each of the spectral bins in Rizzi (1998) have been used. The age for this spectrum obtained from the light curves is 9 days (Bufano et al. 2005), while the age determined spectroscopically if ∼8.4 days (from Harutyunyan et al. 2005).

A version of this tool, identical to the "sfa" by Rizzi (1998) and replicating that of Riess et al. (1997), has also been developed. This version, used for comparison of type-Ia SNe only, determines the spectral feature age (SFA, Riess et al. 1997) of a given type-Ia SN through its comparison with other SNe Ia. For this purpose, a template database of well studied SN Ia spectra, with good temporal coverage and spanning a range of Ia subtypes (SN 1991T- and 1991bg-like) have been selected. For every bin of the input spectrum, the phase of the same bin of the best match template is obtained and, as in Riess et al. (1997), the SFA of the input spectrum is calculated as the weighted mean of these phases. In our version of the tool we use the weights refined by Rizzi (1998).

As an example, in Figure 3.13 the graphical output of the program, showing the comparison of peculiar type-Ia SN 1999cw (Bufano et al. 2005) is displayed. The spectrum of SN 1999cw 9 days after maximum (black line) is overplotted by those of best match templates in each bin. The best match SNe for each bin are reported below, together with the above mentioned weights (see also Harutyunyan et al. 2005).

3.3.2 Normalised spectra comparison tool

In GELATO, to minimise the effects of reddening and errors in continuum flux calibration, we divided the spectra into small bins. On the other hand, one may remove the continuum from the spectra and, thus, attempt to achieve the same goal of comparison of the spectral features relative shapes and intensities with a different algorithm. This is the approach that has been implemented in another tool of the PASSPARTOO collection.

In SN spectra the continuum is not easily determined as in the spectra of hot stars and galaxies, for instance. In our procedure we try to fix the pseudo-continuum performing a least-squares polynomial fit to the SN spectrum. The normalised spectrum is obtained dividing the original one by this continuum. In practice, the polynomial fit is performed twice, the first time using a 5-th degree polynomial and then a degree 3 polynomial. The resulting normalised spectrum is then compared to the templates, which are preprocessed in the same manner.The best fitting template is found through the minimisation of the mean relative distance between the spectra.

Figure 3.14 shows the original and normalised spectra of type-II SN 2004aq. Also, the pseudo-continuum, obtained as described above, is plotted in the figure. Often the discontinuities and noise at the ends of the spectra prevent a correct fitting in those regions. Moreover, the following division by the continuum amplifies these variations, and in the final spectrum these regions are seen as high frequency noise. To avoid the impact of this noise on the calculations of differences, the program checks the presence of such a noise at the spectra extremes (considering a 5% length reduction at both ends) and discards those parts from further calculations.

In Figure 3.15 the output of the program displaying the comparison results for the above mentioned spectrum of type-II SN 2004aq (black line). The best match is the type-II SN 1991al spectrum 25 days after its discovery. The figure shows that once SED is removed, these two spectra result similar. For the original versions of these two spectra see Figure 4.7 (bottom panel), where the differences in SED of the spectra are clearly seen.

The method of the continuum fits used in this tool is simplified and limited, though if performed with

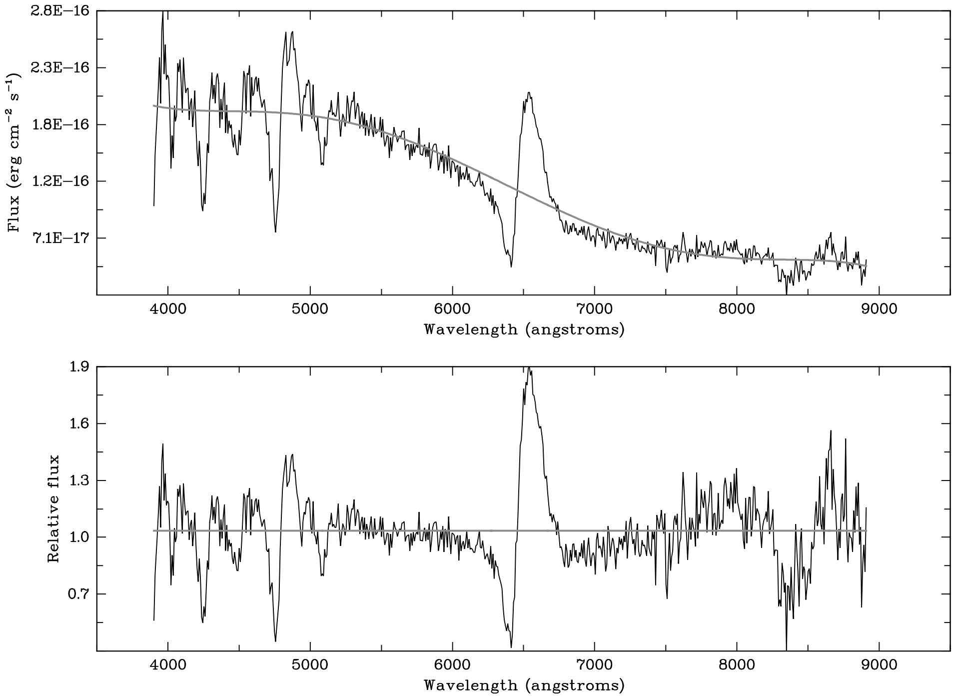


FIGURE 3.14– Top: the spectrum of type-II SN 2004aq (black line) with its pseudo-continuum (gray line), which is obtained by a least-squares polynomial fit to the spectrum. Bottom: the normalised version of the above spectrum (black line) with the constant (equal to 1) pseudo-continuum (gray line).

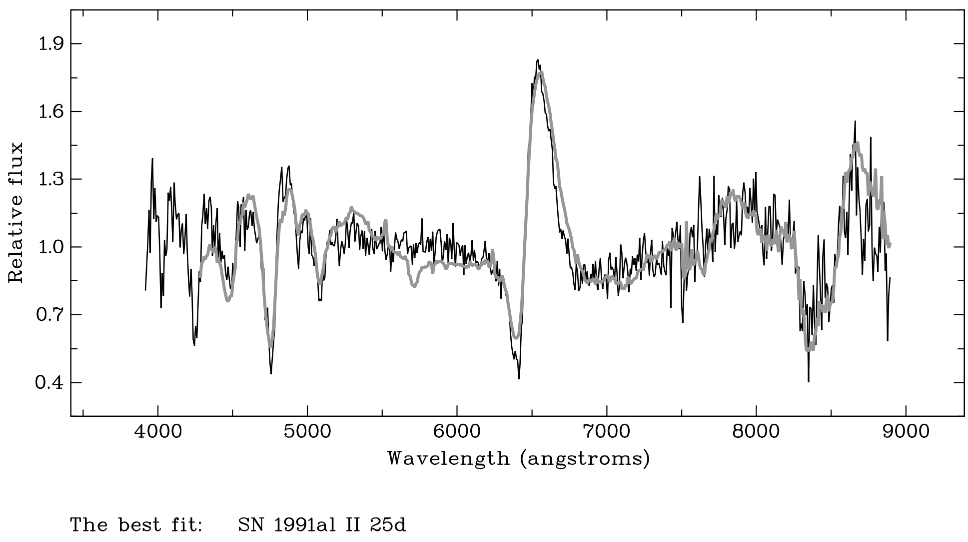


FIGURE 3.15– The output plot of comparison of the normalised spectrum of type-II SN 2004aq (black line) with its best fitting template, the type-II SN 1991al spectrum 25 days after discovery (gray line). The spectra are in the parent galaxy restframe. See also Section 4.1 for a discussion on SN 2004aq and Figure 4.7 for the overplot of the original spectra.

human supervision, it is often possible to effectively fit and remove the continuum. More robust methods of continuum removal in SN spectra have been presented (Blondin & Tonry 2007; Jeffery et al. 2007), where cubic spline fits and boxcar smoothing techniques are implemented.

3.4 Discussion

As already mentioned, a few SN spectra comparison tools have been developed by other groups. The techniques used to perform the comparison are cross-correlation, implemented by (SNID; Blondin & Tonry 2007) or χ^2-like quantity minimisation ("superfit", SN-fit; Howell et al. 2005; Sainton 2004).

These three tools have been developed mainly to be used during high-z SN searches, hence their original aim was the identification of type-Ia SNe in the high-z spectra samples. In general, the redshifts of the host galaxies of these SNe are unknown, thus, these tools determine not only the SN type but also the redshift. This is one of the differences that these tools have in respect to GELATO.

Blondin & Tonry (2007) implemented the algorithm based on correlation techniques of Tonry & Davis in the SNID code. It is used to distinguish between type-Ia and Ib/c SNe and the quality of the correlation between the spectra is quantified allowing the evaluation of the redshift error. The defined quality parameter *r*lap quantifies the reliability of a given correlation. For type-Ia SNe the typical redshift error is $\sigma_z \lesssim 0.01$ and the one on age is $\sigma_t \lesssim 3$ days (Blondin & Tonry 2007).

The other two tools perform the minimisation of a χ^2-like quantity for a number of redshift values and find the best match between two spectra. In "superfit", an elaborate implementation of such an approach, Howell et al. (2005) compare a given SN spectrum to a template SN spectrum contaminated with different amounts of template galaxy spectra. This allows to identify the SN spectra even when it is contaminated by the host galaxy spectra (an issue important in high-z context). SN-fit (Sainton 2004) is a similar program that finds the χ^2 value between a given spectrum and a model spectrum constructed combining a template SN spectra, possibly dereddened in different amounts, and a galaxy spectrum. The best matching SN template-galaxy combination is found through minimisation of the χ^2 values. However, the χ^2 values are strongly affected by the spectra noise, as a consequence they do not provide a useful evaluation of the quality of the best fits for different SN cases (Balland et al. 2006).

Another method of SN spectra comparison was developed by Jeffery et al. (2007). Differently from the above mentioned ones, the aim of this method was the comparative study of SN spectra. After discarding the continuum information from the spectra, using boxcar smoothing techniques, the resulting locally-normalised spectra (spectral line patterns) are compared. The goodness-of-fit tests called DIFF1 and DIFF2 are used to evaluate the similarity of the spectra. DIFF1 essentially measures the mean relative difference between the normalised spectra, while DIFF2 is DIFF1 minimised with respect to a relative wavelength shift between the spectra (Jeffery et al. 2007). These tests are performed to order SNe into empirical groups for further studies.

All these tools, as well as GELATO, perform comparison of SN spectra to achieve different goals. Each of them is optimised for the task it has been designed for. While, GELATO is a fast and flexible tool performing reliable classification of nearby SN spectra (see also Chapter 4), others are more robust for type-Ia SN identification in high-z samples of spectra with a high galaxy contamination. One may note, that in spite of using different techniques, all these tools try to discard as much as possible the information on the shape of the SED in SN spectra. In fact, as already mentioned in Section 3.1.4, the form of the continuum is often misleading in showing the degree of similarity of SN spectra.

The current version of GELATO is routinely used by the members of Padova SN group, providing reliable results and showing satisfactory performance. However, we plan several future improvements to the software.

3.5 Further improvements

Few of the improvements to GELATO have already been mentioned in this chapter. They concern the pre-processing of the spectra, in particular, the smoothing and resampling. The smoothing box size and the step of resampling will become user-accessible parameters, giving the user the possibility to select these values on the basis of the type and the dispersion of the input SN spectra. Other improvements will concern the goodness-of-fit evaluation. More tests will be performed to refine the computation of the GoF and to establish its confidence levels.

The division of spectra in small bins, containing different spectral regions / features, was used to reduce the misleading information coming from the continuum. However, the division in bins has another advantage to be exploited, that of weighting the bins. In the current version of GELATO we treat the bins equally, i.e. all the spectral regions / features have the same weight. Instead, one may assign different weights to the bins, on the basis of the significance of each bin for a given task (classification, ageing). For ageing type-Ia SN this has already been done by Riess et al. (1997); Rizzi (1998) (see Section 3.3.1). Ideally, this can be extended to the spectra classification (and possibly to the ageing of SNe of other types). We will try to implement the dynamic assignment of different sets of weights in GELATO.

As described before, for GELATO the redshift is a required input. This fact had not brought limitations so far, since we concentrated on comparisons of nearby SN spectra, and for almost all nearby SNe the catalogued redshifts of their host galaxies were available. Otherwise the redshift was estimated from the spectrum of the host galaxy. However, taking into account the flexibility of GELATO, the implementation of the input spectrum redshift evaluation is not too difficult. In the new version of the tool, the GoF will be calculated for a number of redshift values separated by discrete intervals.

GELATO will be made accessible to the SN community. A web-based interface to the program is being developed, which will allow users to obtain fast type, phase (and redshift) determination of their own spectra.

4

Science with PASSPARTOO

IN THE PREVIOUS TWO CHAPTERS I described the development of two essential components of an objective SN classification: the SN spectra templates (archive) and the software for automatic comparison of the spectra. The combination of these parts can be used to study the SNe, and in this chapter I describe its applications and present the results.

The first section of this chapter is dedicated to the classification and study of SN spectra obtained during the years of the ESC. Using GELATO I verified the original classification of the objects and provided a detailed description of the spectra. Also the phases of the spectra are estimated by means of the comparison software. The results of this work have been submitted for publication in A&A.

In the second section of this chapter I present our SN classification program at Telescopio Nazionale Galileo. During this program the spectra comparison procedure was widely used, proving to be a fast, secure and useful tool for SN classification. Among the others, two extraordinary SN were identified by this classification program, which immediately became targets of large observational campaigns.

The third section of this chapter presents the material published in Benetti et al. (2006b) regarding SN 2002ic. The nature of this SN has been a subject of debates, and in the above mentioned work we proposed an alternative classification of SN 2002ic. During this study, the objective classification of this SN provided by our spectra comparison software supported this claim.

4.1 ESC Supernova spectroscopy of non-ESC targets*

As mentioned in Section 2.1, the European Supernova Collaboration (ESC) was a European Research Training Network (RTN), founded in 2002 with the goal to improve our understanding of SN Ia physics through a detailed study of nearby SNe Ia. The observational program of the collaboration established criteria for the target selection: the SNe had to be, of course, of type Ia, nearby ($v_{rec} < 6000$ km s^{-1}) and well (about a week) before maximum light. During the following years detailed spectro-photometric monitoring of of 15 nearby SNe Ia (plus 1 SN Ic) was carried out. The results for 7 of these objects

*some material from this chapter will be published in A&A

are already published in dedicated papers. Several other ESC papers with results have been submitted or accepted for publication. Using also ESC SNe Ia, analyses of systematic properties of SNe Ia are presented in Benetti et al. (2005), Mazzali et al. (2005a), Hachinger et al. (2006) and Mazzali et al. (2007).

In order to select ESC target candidates, prompt classification of newly discovered SNe was an essential task. Thereafter some objects became targets of extensive monitoring, many others did not pass the ESC selection criteria and no follow-up observations were triggered. For these SNe only classification spectra are therefore available. These data have not been analysed in detail or published so far although in some cases, they contain interesting information. In this section we present spectra of 36 SNe, obtained during the ESC-related programs, for which follow-up observations were not activated. In particular, some of these spectra (4) were obtained at or before maximum light when unique information about the physical conditions and the chemical structure of the progenitor star can be retrieved. Thus we considered very important to extract any physical information. The spectra have been re-classified using GELATO, also, the ages provided by the tool are presented and discussed. This was the first large application of the software, during which GELATO was used “a posteriori”, providing the best matching template spectra to the input ones. The results of this work have been submitted for publication in A&A.

4.1.1 The sample and the data reduction

The sample of 36 SNe is presented in Table 4.1, where also the information on instrumental configurations and observational details is listed. Seven different telescope+instrument combinations have been used for the observations. The last column of the table contains the references for the discovery and the classification circulars (IAUC, CBET) for each object.

All two-dimensional images were pre-reduced (trimmed, overscan, bias and flatfield corrected) with standard IRAF* subroutines. Further data processing was performed using the procedures from the IRAF CTIOSLIT package.

In particular, optimised extractions of one-dimensional spectra were performed with the APALL task. The galaxy contribution and night sky lines were subtracted through polynomial fits. The one-dimensional spectra were wavelength-calibrated by comparison with spectra of arc lamps obtained during the same night. The lamp spectra (usually He-Ne, Hg-Cd, He-Ar) were taken with the same instrumental configuration as for the SN observation. The wavelength calibration was checked and 0-point corrected against bright night-sky emission lines and in general was 1-2Å accurate.

The SN spectra were then flux-calibrated. The standard stars from the lists of Oke (1990); Hamuy et al. (1992; 1994) were observed with the same instrument, preferably during the same night as the SN. The response curves of the instrumental configurations were obtained via comparison of the observed standard star spectrum with the flux values tabulated for that star. To compensate for the effect of the atmospheric refraction (Filippenko 1982), the spectra were mostly observed with the spectrograph slit oriented on the parallactic angle.

In some cases two spectra of the same object observed during the same night in different spectral ranges were merged into a single spectrum to gain a wider wavelength coverage and/or higher signal-

*Image Reduction and Analysis Facility, http://iraf.noao.edu

TABLE 4.1– The ESC SN sample and observations

SN	Discovery	Acquisition	Instrumentation	Spectral range	Resolution[1]	Reference
	DD/MM/YY	DD/MM/YY	Telescope+Instrument	Å	Å	IAUC / CBET
2002an	22/01/02	05/02/02	1.82m Mt.Ekar+AFOSC	3700 - 7620	25	7805, 7808, 7818, 7828
2002bh	24/02/02	05/03/02	1.82m Mt.Ekar+AFOSC	4000 - 7600	26	7837, 7840, 7844
2002cs	05/05/02	07/05/02	TNG+DOLORES	3500 - 7930	15	7891, 7894
2002dg	31/05/02	15/06/02	ESO NTT+EMMI	3800 - 9330	10	7915, 7922
2002dm	04/05/02	15/06/02	ESO VLT U4+FORS2	4290 - 10250	12	7921, 7923
2002ej	09/08/02	30/08/02	1.82m Mt.Ekar+AFOSC	3800 - 7630	25	7951, 7963
2002hg	28/10/02	02/11/02	CA 2.2m+CAFOS	3600 - 8690	12	8004, 8007
2002hm	05/11/02	06/11/02	CA 2.2m+CAFOS	3500 - 8700	13	8009
2002hy	12/11/02	15/11/02	ESO 3.6m+EFOSC2	3500 - 9820	13	8016, 8019
2003hg	18/08/03	22/08/03	1.82m Mt.Ekar+AFOSC	3800 - 7360	24	8184, 8187, 40
2003hn	25/08/03	26/08/03	ESO 3.6m+EFOSC2	3600 - 9960	13	8186, 8187
2003ie	19/09/03	22/09/03	1.82m Mt.Ekar+AFOSC	4000 - 7440	25	8205, 8207
2004G	19/01/04	21/01/04	CA 2.2m+CAFOS	3500 - 8090	14	8272, 8273
2004aq	02/03/04	10/03/04	NOT+ALFOSC	3900 - 8910	19	8301
2004bs	16/05/04	19/05/04	CA 2.2m+CAFOS	3800 - 8650	12	8341, 66, 8344, 8348
2004cc	10/06/04	14/06/04	NOT+ALFOSC	3500 - 8990	19	8350, 8353
2004dg	19/07/04	21/07/04	1.82m Mt.Ekar+AFOSC	3800 - 7780	25	8375, 8376, 8383
2004dk	30/07/04	03/08/04	CA 2.2m+CAFOS	3500 - 8750	12	8377, 8379, 8404, 75
2004dn	29/07/04	05/08/04	CA 2.2m+CAFOS	3800 - 8690	12	8381
2004fe	30/10/04	02/11/04	NOT+ALFOSC	3500 - 8900	19	8425, 8426
2004go	18/11/04	07/12/04	1.82m Mt.Ekar+AFOSC	3800 - 7580	24	8448, 8450, 8454
2005G	14/01/05	18/01/05	1.82m Mt.Ekar+AFOSC	3600 - 7300	24	8465, 8568
2005H	15/01/05	17/01/05	CA 2.2m+CAFOS	4000 - 8700	10	8467
2005I	15/01/05	18/01/05	CA 2.2m+CAFOS	3800 - 8610	12	8467
2005N	19/01/05	22/01/05	CA 2.2m+CAFOS	3700 - 8600	12	8470
2005V	30/01/05	31/01/05	CA 2.2m+CAFOS	3500 - 8780	14	8474, 8572
2005ab	05/02/05	09/02/05	1.82m Mt.Ekar+AFOSC	4250 - 8070	25	8478, 8479, 8480
2005ai	12/02/05	14/02/05	CA 2.2m+CAFOS	3800 - 8700	12	8486, 8487
2005br	28/03/05	25/05/05	ESO VLT U1+FORS2	4000 - 9710	12	8516, 156, 8538
2005bs	19/04/05	25/05/05	ESO VLT U1+FORS2	3800 - 9290	12	8517, 143, 156, 8538
2005cb	13/05/05	25/05/05	ESO VLT U1+FORS2	3700 - 9720	12	8530, 156, 8538
2005ce	28/05/05	29/05/05	NOT+ALFOSC	3400 - 8800	19	158, 159
2005de	02/08/05	06/08/05	CA 2.2m+CAFOS	3500 - 8640	15	8580, 191, 8581, 193
2005dv	04/09/05	09/09/05	CA 2.2m+CAFOS	3500 - 8710	12	8598, 217, 218
2005dz	10/09/05	12/09/05	NOT+ALFOSC	3400 - 8850	19	222, 225
2005kl	22/11/05	24/11/05	CA 2.2m+CAFOS	4200 - 8750	12	8634, 300, 305

Notes:

[1] measured on the FWHM of the night sky lines when available, otherwise the typical FWHM for the respective telescope-instrument combination is written

1.82m Mt.Ekar + AFOSC - 1.82m Copernico Telescope + Asiago Faint Object Spectrograph and Camera, Asiago, Italy

TNG + DOLORES - 3.5m Telescopio Nazionale Galileo + Device Optimized for the LOw RESolution, La Palma, Spain

ESO NTT + EMMI - 3.5m New Technology Telescope + ESO Multi-Mode Instrument, ESO La Silla, Chile

ESO VLT U1, U4 + FORS2 - 8m Very Large Telescope, Unit 1, 4 + visual and near UV FOcal Reducer and low dispersion Spectrograph 2, ESO Paranal, Chile

CA 2.2m + CAFOS - 2.2m Calar Alto Telescope + Calar Alto Faint Object Spectrograph, Almería, Spain

ESO 3.6m + EFOSC2 - 3.6m Telescope + ESO Faint Object Spectrograph and Camera (v.2), ESO La Silla, Chile

NOT + ALFOSC - Nordic Optical Telescope + AndaLucia Faint Object Spectrograph and Camera, La Palma, Spain to-noise ratio (SNR). During the analyses of the spectra (line identifications, expansion velocity calculations, etc) the corresponding redshift corrections have been applied.

4.1.2 Results and individual spectra

We compared the spectra of our sample to the templates database using GELATO (see Section 3.1). As already described, the tool finds the best fitting template spectrum to the given one and provides the GoF value of the comparison (see Section 3.1.4). I remind that for GoF values greater or equal to 1.4 the classification is safe, GoF less than 1 indicates that the comparison gives a SN of different type (i.e. erroneous classifications). For GoF values in the range $1 \leq \text{GoF} < 1.4$ the classification varies from fair to erroneous. The results of the comparison of our set of 36 spectra with the templates are summarised in Table 4.2, which lists for each object the best template, the phase of the best template and the GoF.

As it is shown in the table, most of the SNe in our sample are CC SNe. It is not surprising, since the ESC program was focused on the thermonuclear explosions. Nevertheless, several objects are of type Ia, but they either are too distant or discovered at phases later than ∼-5 days, i.e. they did not satisfy the RTN requirements. However, our detailed analyses show that there are at least two objects that would become ESC targets, if there were a spectra comparison software like ours and an appropriate template database was available. This gives more value to our efforts for objective classifications.

Figures 4.1 - 4.18 show the plots of the spectra of our objects together with their best match templates. In the figures the best fitting templates are scaled in flux to match those of the corresponding input spectra. The spectra are shown in the parent galaxy restframe and are not corrected for extinction. Below I present a short discussion on the individual objects.

SN 2002an was found on Jan. 22.52 by Nakano et al. (2002) and classified as a type-II supernova by Benetti et al. (2002c). The spectrum consists of a blue continuum with P-Cyg profiles of H Balmer and He I lines superimposed. H_α is almost purely in emission (Fig. 4.1 top). The GoF is not high (1.7), which is due to some discrepancies in the fit. In particular H_α is not well fitted. The most similar template spectrum is that of the type-II SN 1996bw obtained 7 days after its discovery (ASA, Benetti & Turatto 1996). In some cases (included this one) the explosion or maximum epoch is not estimated for the best fitting templates. Thus, in those cases, we provide information (including the spectrum phase) on the second best matching template. For SN 2002an, the spectrum of another type-II SN 1995ad 12 days after its explosion (Pastorello 2003) also provides a satisfactory fit. The expansion velocities deduced from the minima of He I, H_β and H_γ lines are 9300, 9690 and 9800 km s^{-1}, respectively.

SN 2002bh was found on Feb. 24.3 by Ganeshalingam & Li (2002). Benetti et al. (2002b) classified it as a type-II supernova. A broad H_α emission line is the only strong feature in the noisy spectrum. Also, broad He I, Fe II and H_β features can be identified (Fig. 4.1 bottom). From the minimum of H_α an expansion velocity of about 12000 km s^{-1} is derived. The best fit is with the type-II SN 1995V spectrum (ASA) 8 days after the explosion (Fassia et al. 1998). The template spectrum does not match well the blue slope of the spectrum, possibly because of some reddening in the host galaxy.

SN 2002cs was discovered on May 5.5 by Ganeshalingam et al. (2002). The spectrum is that of a type-Ia supernova, and Riello et al. (2002b) gave an age estimate of 2 ± 2 days before maximum light (Fig. 4.2 top). The expansion velocity deduced from the Si II λ6355 minimum is about 15800 km

TABLE 4.2– The results of comparison of the ESC spectra with GELATO. Best match template phases are relative to the B-maximum epoch for type-Ia and Ib/c SNe and to explosion epoch for type-II SNe.

SN	Type	Best match SN template	GoF	Template phase (days)	Template spectrum reference	Phase reference
2002an	II	1996bw	1.7	7 *	ASA, Benetti & Turatto (1996)	1995ad, 12d - Pastorello (2003)
2002bh	II	1995V	1.4	8	ASA	Fassia et al. (1998)
2002cs	Ia	2004dt	1.6	-7	Altavilla et al. (2007)	
2002dg	Ib	1998dt	1.7	15 **	ASA	Matheson et al. (2001)
2002dm	Ia	1994ae	9.1	92	ASA	
2002ej	II	1995ad	2.9	24	Pastorello (2003)	
2002hg	II	1999em	2.4	41	Elmhamdi et al. (2003)	
2002hm	II	1998ce	3.8	10 *	ASA, Patat & Turatto (1998)	1995ad, 12d - Pastorello (2003)
2002hy	IIb	2001gh	1.4	11 *	ASA, Altavilla et al. (2001)	1993J, 4d - Barbon et al. (1995)
2003hg	II	1995V	2.1	8	ASA	Fassia et al. (1998)
2003hn	II	1995ad	2.4	10	Pastorello (2003)	
2003ie	II	1998A	1.2	37	Pastorello et al. (2005a)	
2004G	II	1993S	2.4	90 *	ASA	1995ad, 100d - Pastorello (2003)
2004aq	II	1991al	2.9	25 *	ASA	2001du, 18d - Smartt et al. (2003)
2004bs	Ib	1998dt	2.0	17 **	ASA	Matheson et al. (2001)
2004cc	Ic	1994I	1.4	10	Filippenko et al. (1995)	
2004dg	II	2001du	4.8	18	Smartt et al. (2003)	
2004dk	Ic	2004aw	1.4	4	Taubenberger et al. (2006)	
2004dn	Ic	2004aw	1.4	4	Taubenberger et al. (2006)	
2004fe	Ic	1994I	1.9	-3	Filippenko et al. (1995)	
2004go	Ia	1996X	2.2	24	Salvo et al. (2001)	
2005G	Ia	1994D	3.5	11	Patat et al. (1996)	
2005H	II	2002gd	1.0	6	Pastorello (2003)	
2005I	II	2003gd	3.3	101	ASA	Hendry et al. (2005)
2005N	Ib	1990I	2.1	88	Elmhamdi et al. (2004)	
2005V	Ic	2004aw	1.3	22	Taubenberger et al. (2006)	
2005ab	II	1997du	1.5	26 *	ASA, Patat (1997)	
2005ai	Ia	1994D	2.7	24	Patat et al. (1996)	
2005br	Ib	1997X	1.9	40	ASA	1990U, 48d - Piemonte (1996)
2005bs	Ia	1996X	3.3	31	Salvo et al. (2001)	
2005cb	Ic	1994I	2.5	1	Filippenko et al. (1995)	
2005ce	Ib/c	1996aq	2.0	5 *	ASA	1994I, 10d - Filippenko et al. (1995)
2005de	Ia	2005cf	2.8	-5	Garavini et al. (2007)	
2005dv	Ia	2002bo	2.9	0	Benetti et al. (2004b)	
2005dz	II	2007T	1.4	4 *	ASA, Benetti et al. (2007b)	2002gd, 6d - Pastorello (2003)
2005kl	Ic	2004aw	1.2	4	Taubenberger et al. (2006)	

Notes:

* spectral epoch relative to the discovery date. In these cases no reference of the explosion epoch is found and, when available, the second best fitting template spectrum with phase relative to the explosion epoch is reported in the "Phase reference" column.

** relative to the R-maximum

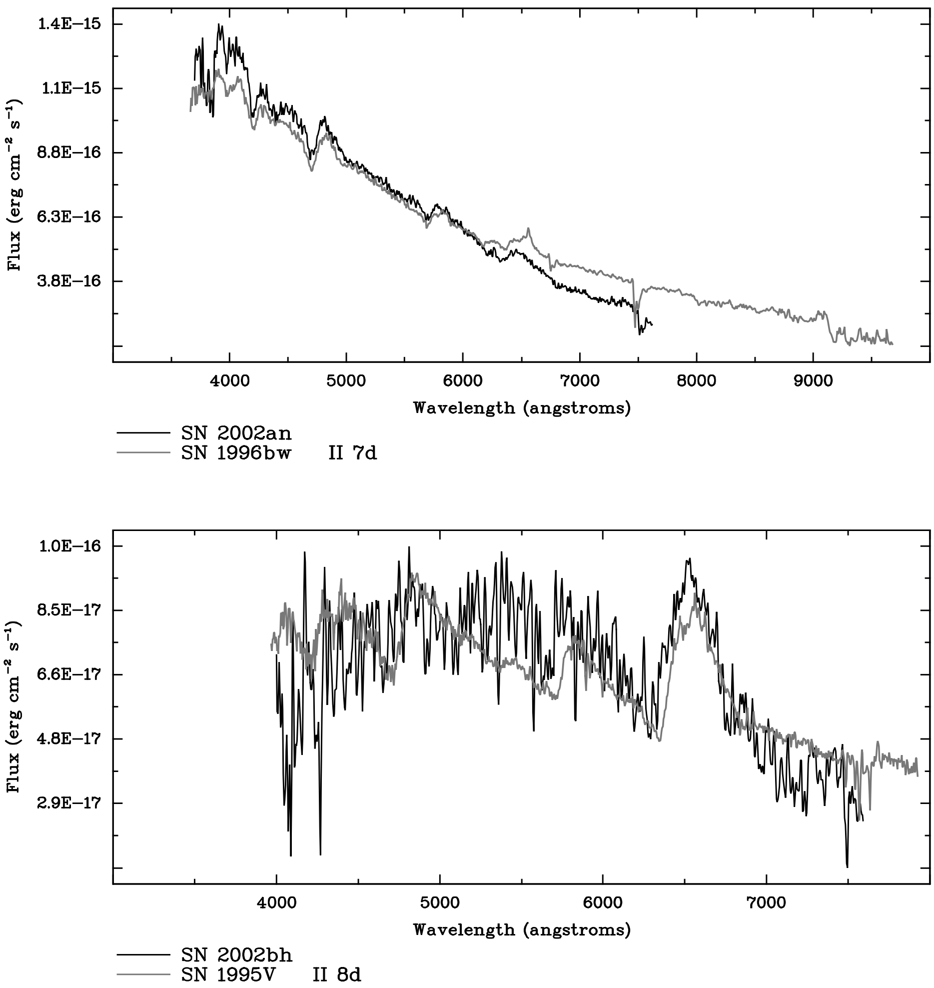


FIGURE 4.1– The comparison of the ESC SN spectra of non-ESC targets with their best fitting templates. The spectra are in the parent galaxy restframe and not corrected for extinction. The black lines are the ESC spectra, while the gray ones display template spectra. Top: SN 2002an, bottom: 2002bh.

s^{-1}. Both the expansion velocity and the age estimates are in agreement with those by Matheson et al. (2002). The high expansion velocity may be caused by contamination by a high-velocity component (see Mazzali et al. 2005a). High-velocity features are known to be particularly strong and blended with the photospheric components in the SNe that belong to the high velocity gradient (HVG) group (see Benetti et al. 2005). In fact, the closest match we found is with the HVG SN 2004dt at a phase of -7 days (Altavilla et al. 2007). The shape of the continuum and interstellar absorption Na I D feature (found in the Galaxy restframe) of the spectrum suggest the presence of significant extinction. The value of GoF = 1.6 is mainly due to a mismatch in the line velocity suggesting either an even more extreme case of HVG SN than SN 2004dt or an earlier phase. Because of the first phase determination (2 $\pm$ 2 days instead of -7 here found) SN 2002cs was unfortunately not considered worth of detailed follow-up by the ESC.

SN 2002dg was found on May 31.3 by Wood-Vasey et al. (2002) and classified as a type-Ib supernova

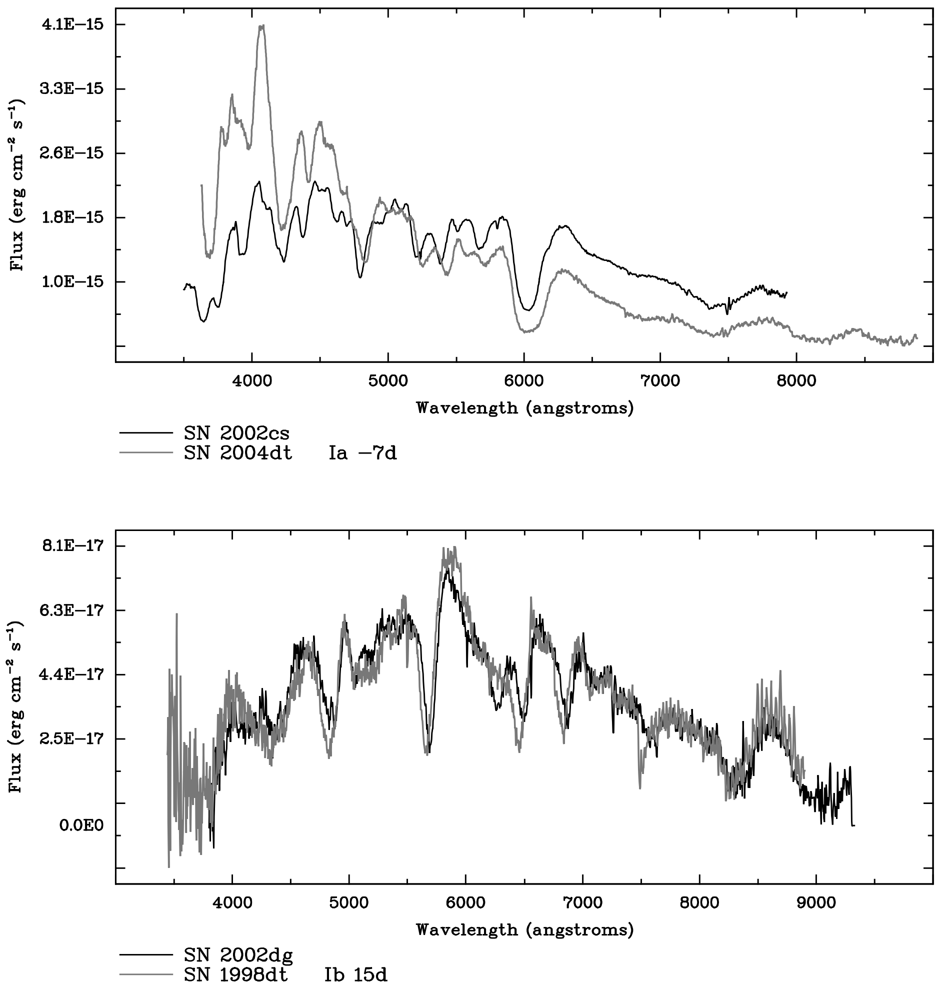


FIGURE 4.2– Same as Figure 4.1 for SN 2002cs (top) and SN 2002dg (bottom).

2-3 weeks after maximum by Riello et al. (2002a). The spectrum (Fig. 4.2 bottom) is most similar to that of the type-Ib SN 1998dt at 15 days from R-band maximum (Matheson et al. 2001). For SN 2002dg, adopting a recession velocity of 14000 km s^{-1} derived by Riello et al. (2002a) from the parent galaxy emission lines, the expansion velocities measured from the He I absorption minima of the SN 2002dg and 1998dt spectra are 9500 and 10900 km s^{-1}, respectively. The largest mismatch to the SN 1998dt spectrum is the absorption at 6270Å (rest frame). If this feature is due to H_α (see Branch et al. 2002), a transitional type-IIb event may be an alternative classification. Inspection of the fit (see Figure 4.2 bottom) shows that not only the He I features, but also other lines in the spectrum of SN 2002dg are slightly narrower than in SN 1998dt.

SN 2002dm was found on May 4.76 by Sanders (2002), Turatto et al. (2002) classified it as a type-Ia SN, giving a phase estimate of about 50 days after maximum light. The high SNR spectrum (Fig. 4.3 top) is almost identical to that of SN 1994ae (from ASA) at 92 days after maximum light. The large number of features present in the spectrum and the exceptional resemblance to the 1994ae spectrum lead

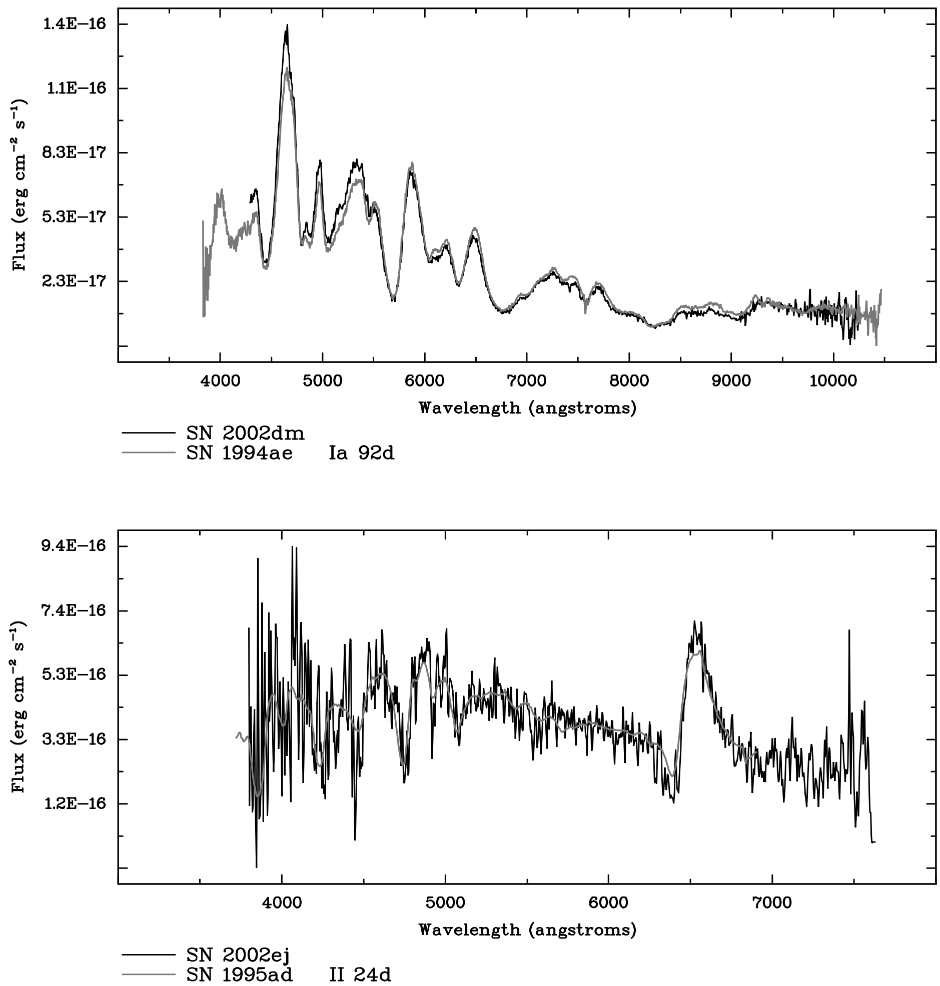


FIGURE 4.3– Same as Figure 4.1 for SN 2002dm (top) and SN 2002ej (bottom).

to the best match among the SNe of the sample (GoF = 9.06).

SN 2002ej was discovered on Aug. 9.11 by Puckett & Kerns (2002) and classified as a type-II supernova two weeks after maximum by Desidera et al. (2002). On the noisy spectrum P-Cyg profiles of H Balmer, Fe II and (possibly) Sc II lines are present (Fig. 4.3 bottom). The best fitting template (GoF = 2.94) is the one of the type-IIP SN 1995ad at 24 days after explosion epoch (Pastorello 2003). The expansion velocity of SN 2002ej deduced from the minimum of H_α line is about 8070 km s^{-1}.

SN 2002hg was found on Oct. 28.22 by Boles & Schwartz (2002) and classified as a type-II supernova few weeks past maximum light by Pignata et al. (2002b). The spectrum shows strong P-Cyg profiles of H Balmer, Fe II, Ca II, Na I, O I, Sc II, Ba II lines (Fig. 4.4 top) and is well-fitted (GoF = 2.4) by a type-II SN 1999em spectrum taken 41 days after explosion (Elmhamdi et al. 2003). The expansion velocity of SN 2002hg deduced from the H_α line profile is about 6900 km s^{-1}.

SN 2002hm was detected on Nov. 5.16 by Boles (2002) and classified as a type-II supernova 30 days after maximum light by Pignata et al. (2002a). The rather blue continuum is overimposed by P-Cyg

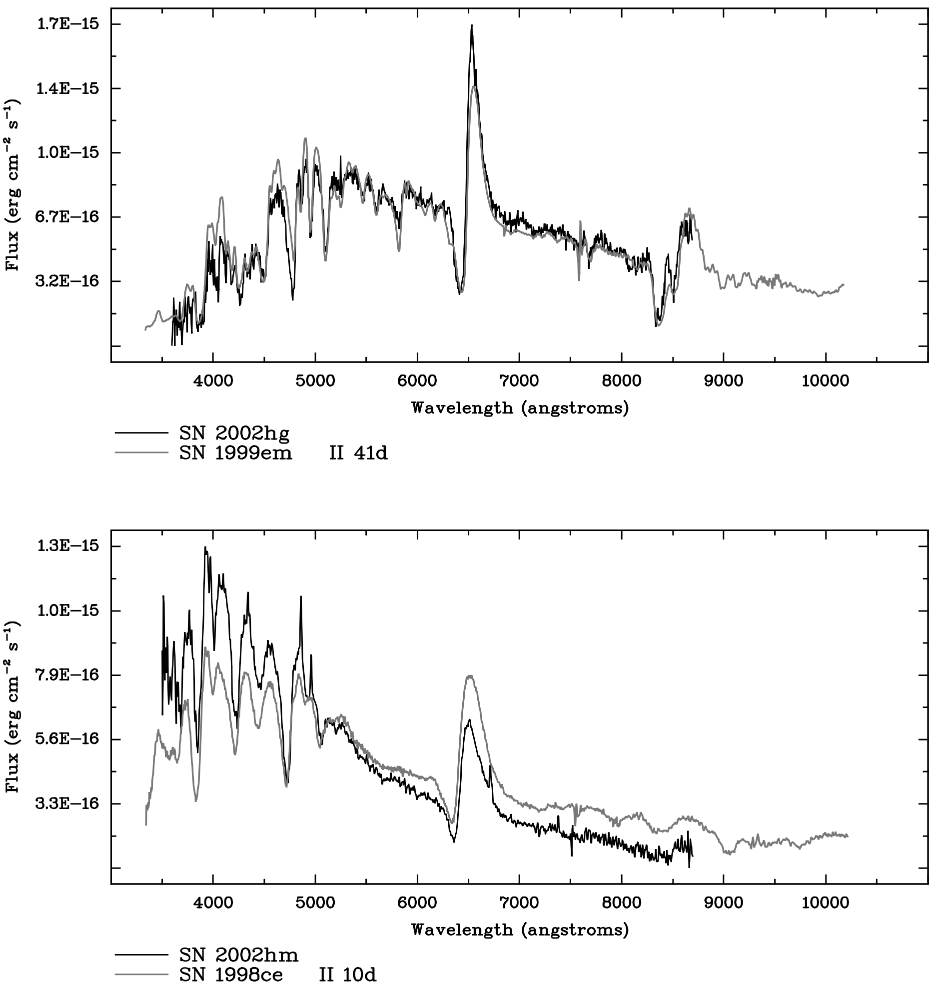


FIGURE 4.4– Same as Figure 4.1 for SN 2002hg (top) and SN 2002hm (bottom).

profiles of H Balmer, Fe II, Ca II lines (Fig. 4.4 bottom). The best fit to this spectrum is provided by the type-II SN 1998ce spectrum at 10 days after discovery (ASA, Patat & Turatto 1998). The SN 2002hm spectrum is also well fitted by SN 1995ad 12 days after explosion (Pastorello 2003), in agreement with the fact Na I D feature is still missing, thus suggesting an earlier phase than that proposed by Pignata et al. (2002a). The expansion velocities deduced from the H_α and H_β absorption minima in the SN 2002hm spectrum are about 9500 and 8100 km s^{-1}, respectively.

SN 2002hy was found on Nov. 12.1 by Monard (2002) and classified as a peculiar type-Ib supernova by Benetti et al. (2002a). The blue continuum is overimposed with strong He I lines at $\lambda\lambda$3889, 4471, 5015, 5876, 6678, 7065 (Fig. 4.5 top). As Benetti et al. (2002a) mentioned, the He I emission peaks are blueshifted on average by 1800 km s^{-1}. Despite the peculiarity of the object, GELATO finds a matching spectrum that contains the He I features with similar line velocity. The best fit to this spectrum is given by the type-II SN 2001gh 11 days after discovery (ASA, Altavilla et al. 2001; Valenti 2003). The second best fitting template is the type-IIb SN 1993J at 4 days after explosion (Barbon et al. 1995), which,

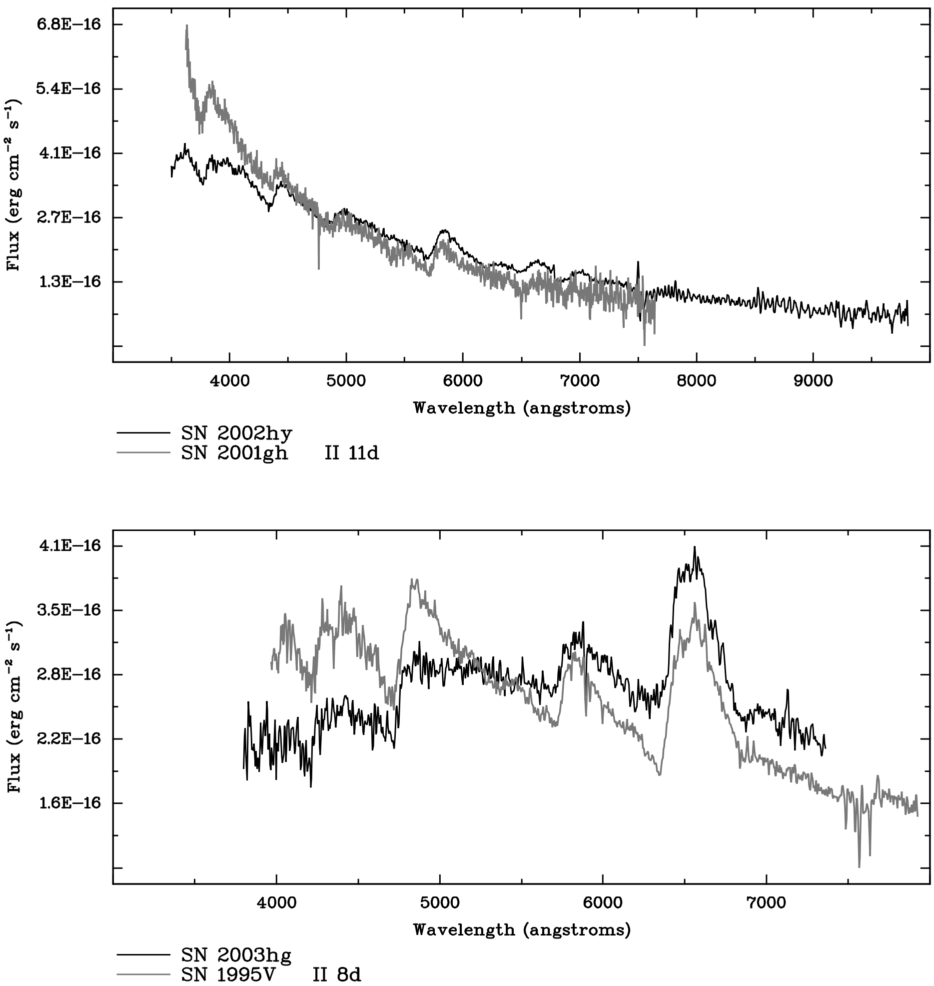
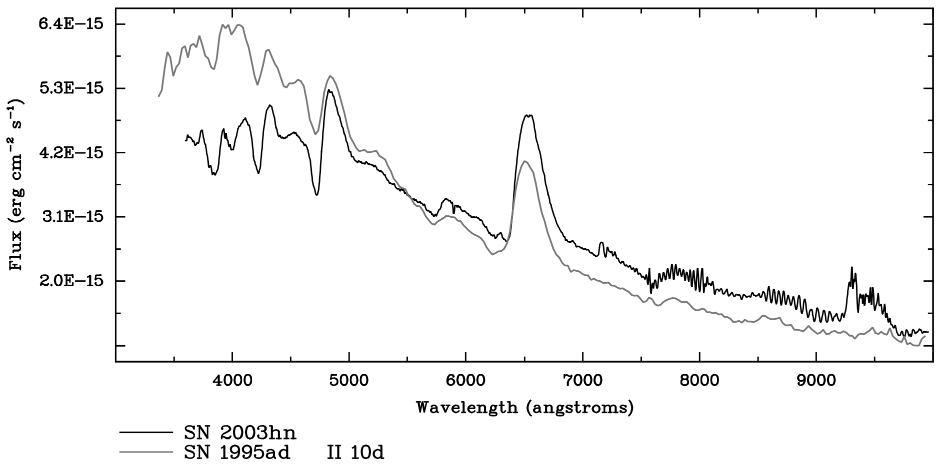


FIGURE 4.5– Same as Figure 4.1 for SN 2002hy (top) and SN 2003hg (bottom).

however, fails to reproduce most of the He I features. SN 2001gh is classified as a type-II SN (Altavilla et al. 2001), but because of the presence of strong He lines both SN 2002hy and SN 2001gh should be considered IIb/Ib events.

SN 2003hg was discovered on Aug. 18.4 by Moore & Li (2003) and classified as a type-II supernova shortly after explosion (Elias-Rosa et al. 2003). Broad emission lines of H_α (possibly with a boxy profile), and He I λ5876 are present together with absorptions of H_β, and H_γ (Fig. 4.5). The best fit to this spectrum is with that of the type-II SN 1995V 8 days after explosion (ASA, the same as in SN 2002bh case). Despite the different SED, most probably due to reddening (EW(Na I D) $\approx$ 1.3Å for SN 2003hg), the GoF is high (2.09). This is one of the best proofs that GELATO is little sensible to the reddening, as described in Section 3.1.

SN 2003hn was found on Aug. 25.7 by Evans et al. (2003) and classified as a type-II supernova approximately two weeks after explosion by Salvo et al. (2003). The spectrum has a blue continuum and P-Cyg profiles of the H_β, H_γ and He I λ5876 lines. H_α is present almost purely in emission (Fig.



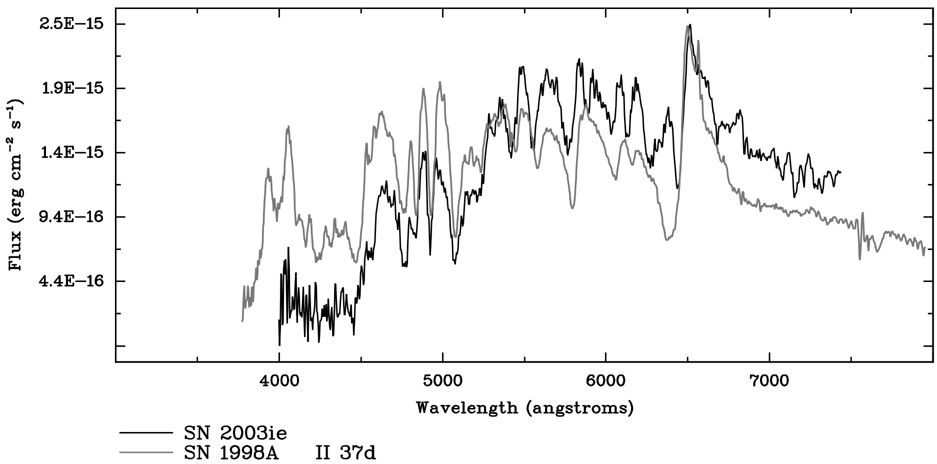


FIGURE 4.6– Same as Figure 4.1 for SN 2003hn (top) and SN 2003ie (bottom).

4.6 top). The best match of this spectrum is the type-II SN 1995ad spectrum 12 days after explosion date (Pastorello 2003). The interstellar Na I D absorption feature present in the SN 2003hn spectrum suggests some reddening (EW(Na I D) $\approx$ 0.62Å, corresponding to a lower limit of E(B−V)=0.089mag, see Turatto et al. 2003). The expansion velocities for SN 2003hn deduced from the H_β and H_γ lines are of about 8700 and 8200 km s^{-1}, respectively.

SN 2003ie was found on Sept. 19.8 by Arbour & Boles (2003) and classified as a type-II supernova by Benetti et al. (2003). P-Cyg profiles of H_α, H_β, Fe II, Sc II, Na I D and Ba II lines are overimposed on red continuum (Fig. 4.6 bottom). The expansion velocity deduced from the H_α absorption minimum is about 5500 km s^{-1}. The best fit to this spectrum is with that of the peculiar type-II SN 1998A 37 days after explosion (Pastorello et al. 2005a). Like in SN 1998A the H_α emission shows a significant shift of about 2100 km s^{-1} towards the blue. This effect is seen also in SN 1987A and in other type-II SNe (see Pastorello et al. 2005a; for discussion).

SN 2004G was found on Jan. 19.8 by Nakano et al. (2004) and classified as a type-II supernova

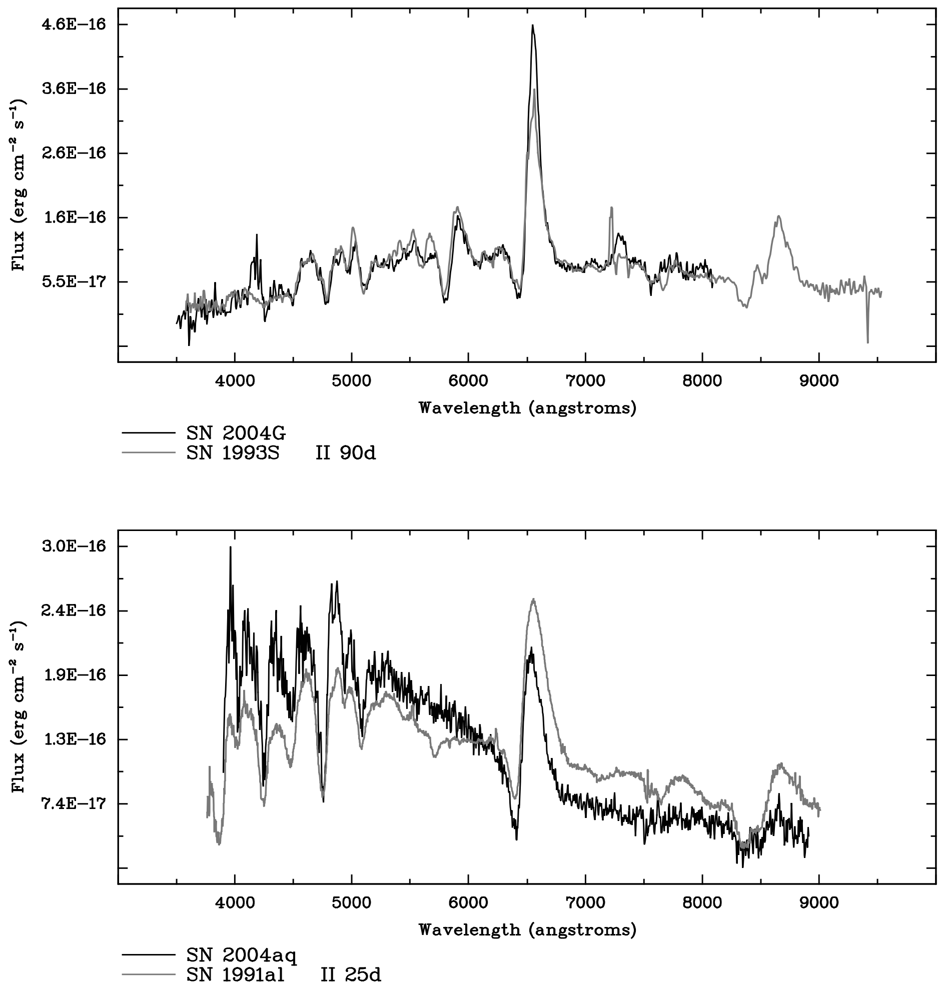


FIGURE 4.7– Same as Figure 4.1 for SN 2004G (top) and SN 2004aq (bottom).

about 5 months after explosion by Elias-Rosa et al. (2004b). The best fit to the SN 2004G spectrum (Fig. 4.7 top) is with the type-II SN 1993S 90 days after its discovery (ASA). The spectrum is well-fitted also by the type-II SN 1995ad spectrum 100 days past explosion (Pastorello 2003). The expansion velocities deduced from the H_α and H_β absorption minima are about 6700 and 4900 km s^{-1}, respectively.

SN 2004aq was discovered on Mar. 2.1 by Armstrong & Buczynski (2004) and classified as a type-II supernova one month after explosion by Elias-Rosa et al. (2004a). The spectrum shows P-Cyg profiles of H_α, H_β, Ca II and Fe II lines overimposed on a rather blue continuum (Fig. 4.7 bottom). The best fit to this spectrum is a type-II SN 1991al spectrum taken 25 days after discovery (ASA). The minima of the H_α and H_β absorption components on the SN 2004aq spectrum are blueshifted by about 7700 and 6600 km s^{-1}, respectively, very similar to those of SN 1991al (7700 and 6500 km s^{-1}). The spectrum of SN 2004aq is also well fitted by that of the type-II SN 2001du 18 days after explosion (Smartt et al. 2003).

SN 2004bs was found on May 16.9 by Armstrong (2004) and classified as a type-Ib supernova about

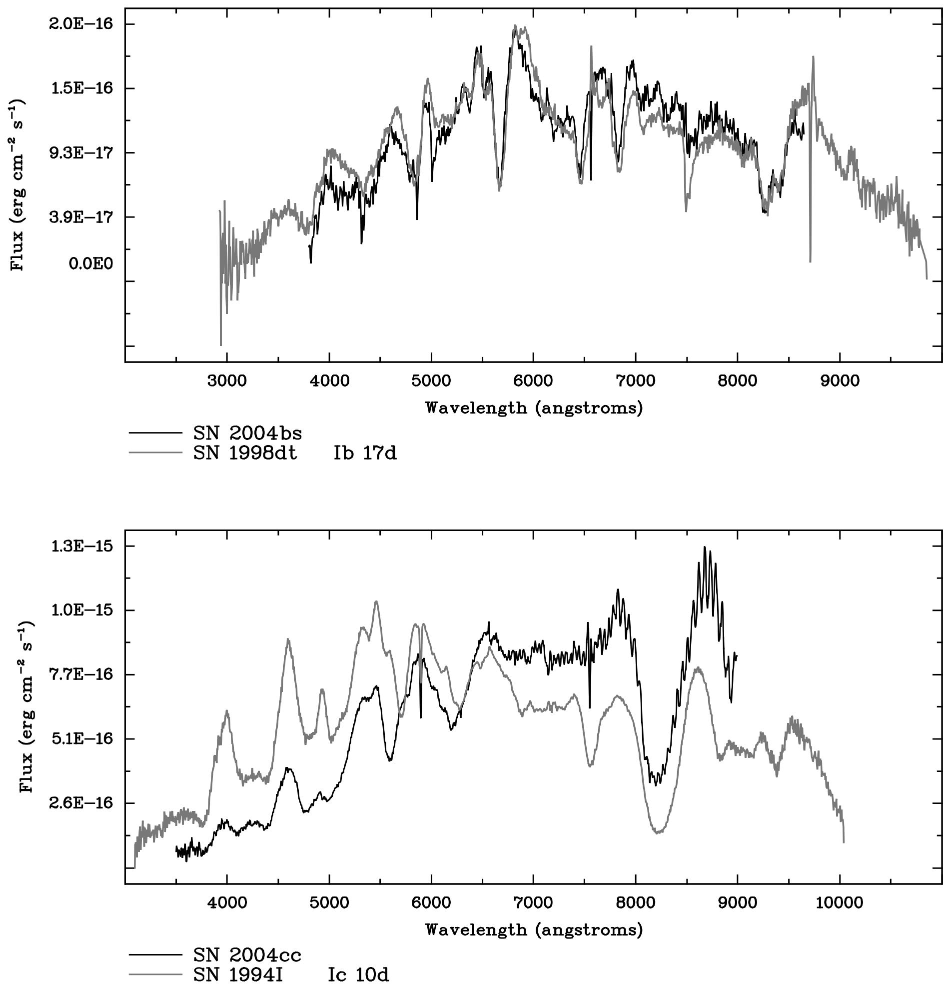


FIGURE 4.8– Same as Figure 4.1 for SN 2004bs (top) and SN 2004cc (bottom).

3 weeks past maximum by Pignata et al. (2004). The spectrum is dominated by He I λ5876, 6678, 7065 lines with velocities of about 10600, 10100 and 10000 km s^{-1}, respectively (Fig. 4.8 top). Lines of Fe II, O I and Ca II are also present in the spectrum. The best matching template is the type-Ib SN 1998dt (ASA), 17 days after R-band maximum (Matheson et al. 2001). The phase estimate done by Pignata et al. (2004) is similar to the one obtained from the best match template found by GELATO, while the derived expansion velocities ($\sim$ 10000 km s^{-1}) are too high for such an age.

SN 2004cc was found on Jun 10.3 by Monard & Li (2004) and classified as a type-I supernova by Matheson et al. (2004) and type-Ic supernova one week before maximum by Foley et al. (2004). P-Cyg profiles of Fe II, Na I D (possibly blended with He I λ5876), Si II and Ca II are present on the highly reddened spectrum (Fig. 4.8 bottom). Strong Na I D interstellar absorption is detected in the host galaxy restframe (EW $\approx$ 4.1Å). The best fit to this spectrum is provided by the type-Ic SN 1994I 10 days after B maximum (Filippenko et al. 1995), although the Na I D (+ He I) absorption and Fe II features in SN 2004cc are bluer (i.e. with a higher expansion velocity) than those of SN 1994I. The deep O I feature in the SN 1994I spectrum in not present in SN 2004cc, making this object rather peculiar.

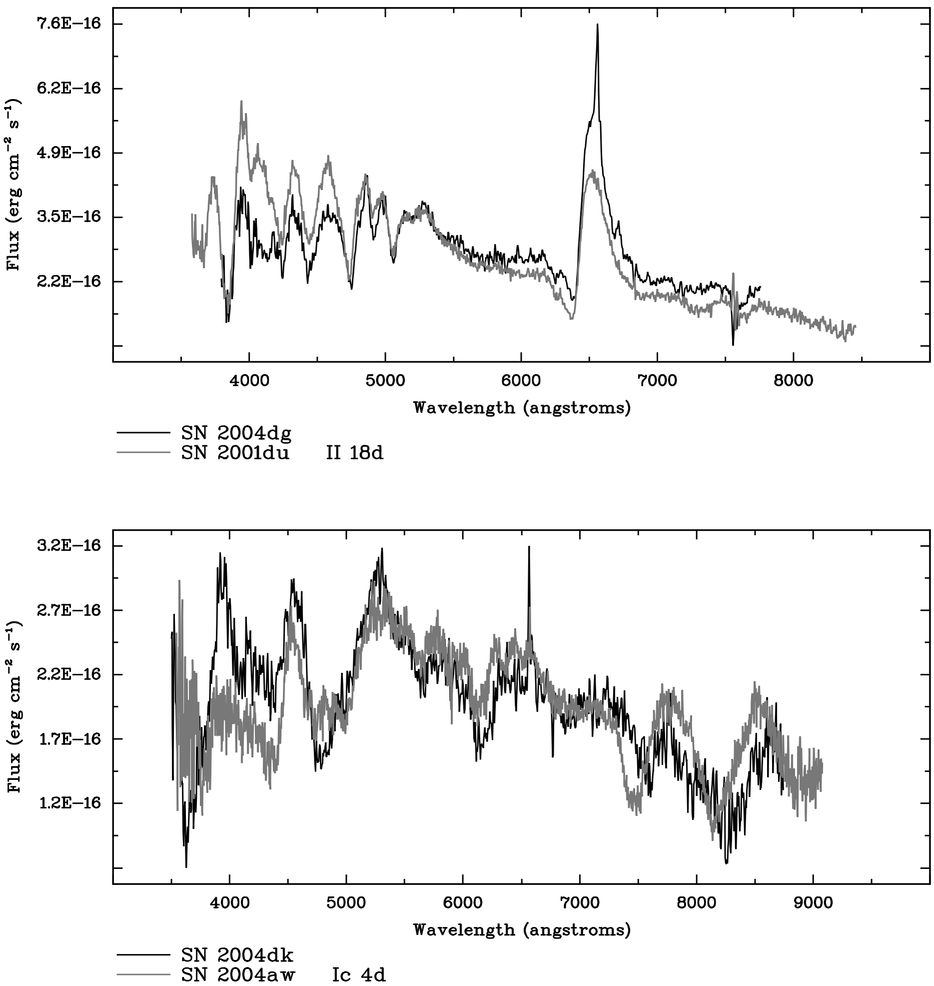


FIGURE 4.9– Same as Figure 4.1 for SN 2004dg (top) and SN 2004dk (bottom).

SN 2004dg was discovered on Jul 19.8 by Vagnozzi et al. (2004) and classified as a type-II supernova by Elias et al. (2004). The spectrum shows P-Cyg profiles of H_α, H_β, Ca II H&K, Fe II and Ti II lines (Fig. 4.9 top). There is a narrow emission component, probably due to a nearby H II region, on the broad H_α emission profile. The recession velocity deduced from this narrow emission line is of about 1760 km s^{-1}. Adopting this recession velocity, the photospheric velocities deduced from H_α and H_β are about 8420 and 6970 km s^{-1}, respectively. The spectrum of the type-II SN 2001du 18 days from explosion (Smartt et al. 2003) is the best match. Our algorithm provides a very high GoF = 4.76, despite a stronger H_α emission in SN 2004dg and a slight difference in SED, probably caused by reddening. In fact, on the noisy continuum a clear Na I D interstellar absorption feature with EW $\approx$ 1.9Å is detected, corresponding to E(B-V) = 0.29 mag (Turatto et al. 2003).

SN 2004dk was found on Aug 1.2 by Graham & Li (2004a) and classified as a type-Ic supernova by Patat et al. (2004a). P-Cyg profiles of Ca II, Fe II, Na I, Si II and O I lines are present in the spectrum

(Fig. 4.9 bottom). The spectrum is similar to that of the type-Ic SN 2004aw 4 days after B maximum light (Taubenberger et al. 2006), though the O I and Ca II absorption profiles of the SN 2004aw spectrum are significantly bluer than those of 2004dk. The absorption minima of Si II 6355Å and O I 7774Å in the SN 2004dk spectrum suggest expansion velocities of about 9200 and 7300 km s^{-1}, respectively. A narrow H_α emission probably due to a nearby H II region is present. The second best fit to this spectrum is by that of SN 1994I 3 days before maximum light (Filippenko et al. 1995), as mentioned in Patat et al. (2004a).

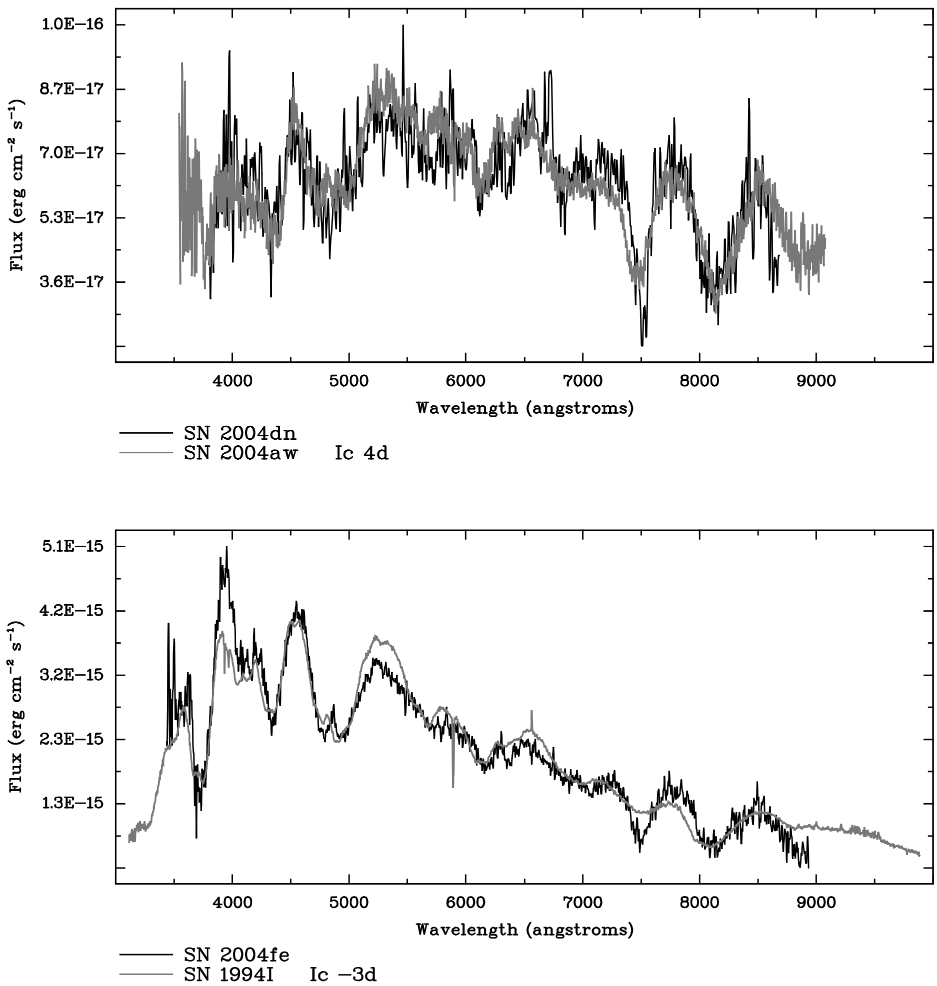


FIGURE 4.10– Same as Figure 4.1 for SN 2004dn (top) and SN 2004fe (bottom).

SN 2004dn was discovered on Jul. 29.4 by Graham & Li (2004b) and classified as a type-Ic supernova few days before maximum light by Patat et al. (2004b). Spectral features of Si II, O I and Ca II are clearly visible (Fig. 4.10 top). The expansion velocities deduced from Si II 6355Å and O I 7774Å minima are of about 10500 and 10200 km s^{-1}, respectively. The best fitting template is again that of the type-Ic SN 2004aw 4 days after maximum (Taubenberger et al. 2006). Having the same best fitting template means that the spectra of SN 2004dn and 2004dk are also similar.

SN 2004fe was discovered on Oct. 30.3 by Pugh et al. (2004) and classified as a type-Ic supernova a few days before maximum by Modjaz et al. (2004). The spectrum (Fig. 4.10 bottom) shows P-Cyg profiles of Ca II, Fe II, Na I D, and O I lines. The best fitting template spectrum is that of the type-Ic SN 1994I 3 days before B maximum (Filippenko et al. 1995). The absorption at about 6170Å is probably due to Si II λ6355, while the one at about 6360Å is possibly either weak H_α or C II.

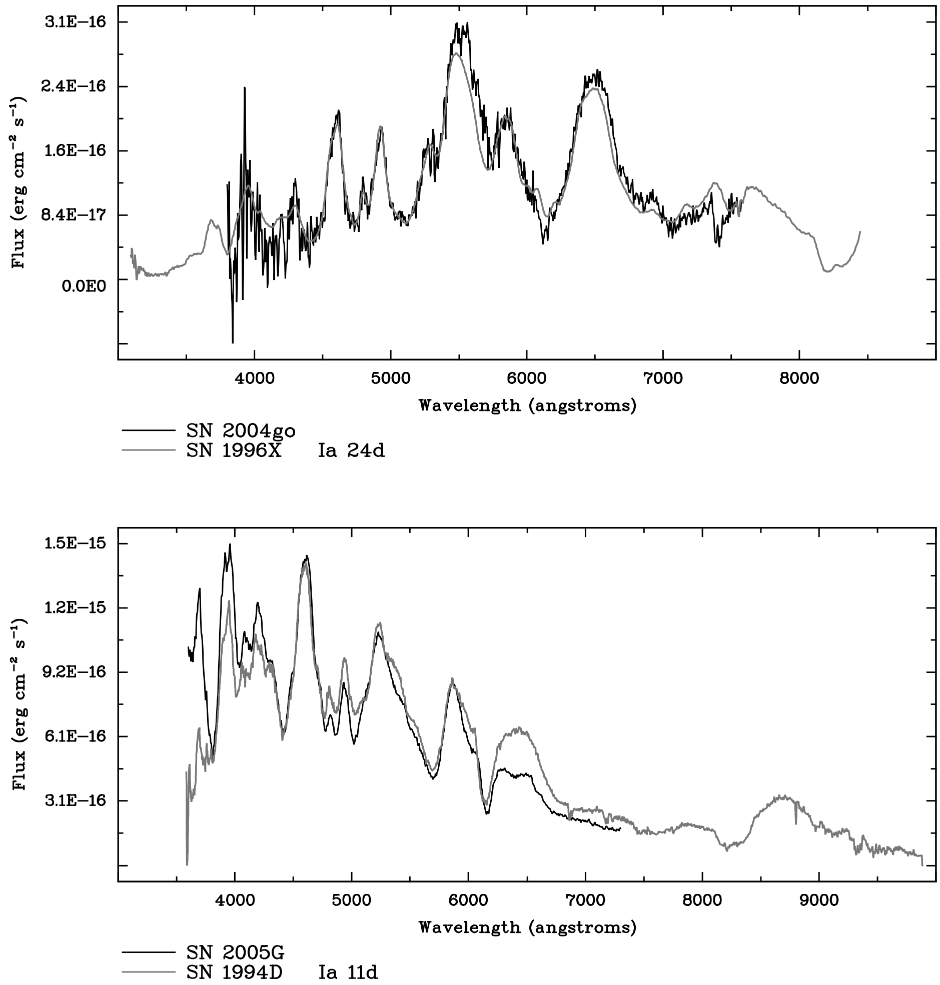


FIGURE 4.11– Same as Figure 4.1 for SN 2004go (top) and SN 2005G (bottom).

SN 2004go was found on Nov. 18.3 by Li et al. (2004) and classified as a type-Ia supernova 3-4 weeks past maximum by Navasardyan et al. (2004). The expansion velocity deduced from Si II 6355Å absorption minimum is about 10200 km s^{-1}. The spectrum (Fig. 4.11 top) is very similar to that of the type-Ia SN 1996X 24 days after maximum light (Salvo et al. 2001). The spectra of SN 1994D (Patat et al. 1996) and 2002bo (Benetti et al. 2004b) 24 and 28 days after their B band maxima also provide good fits.

SN 2005G was found on Jan. 14.6 by Graham et al. (2005a) and classified as a type-Ia supernova about 10 days past maximum by Navasardyan et al. (2005). Ganeshalingam et al. (2005) report that a spectrum of SN 2005G taken 2 days before ours shows a narrow Si II 6355Å absorption, a blend of two S II absorptions around 5500Å and a flux density drop blueward of Ca II H&K lines. The Si II and S II features peculiarities are present in our spectrum as well (Fig. 4.11 bottom), but we cannot confirm the blue flux decline, because of the limited spectral range. Nevertheless, the spectrum closely resembles (GoF = 3.5) that of the type-Ia SN 1994D 11 days after maximum light (Patat et al. 1996). The blueshift of Si II 6355Å minimum is of 9600 km s^{-1}.

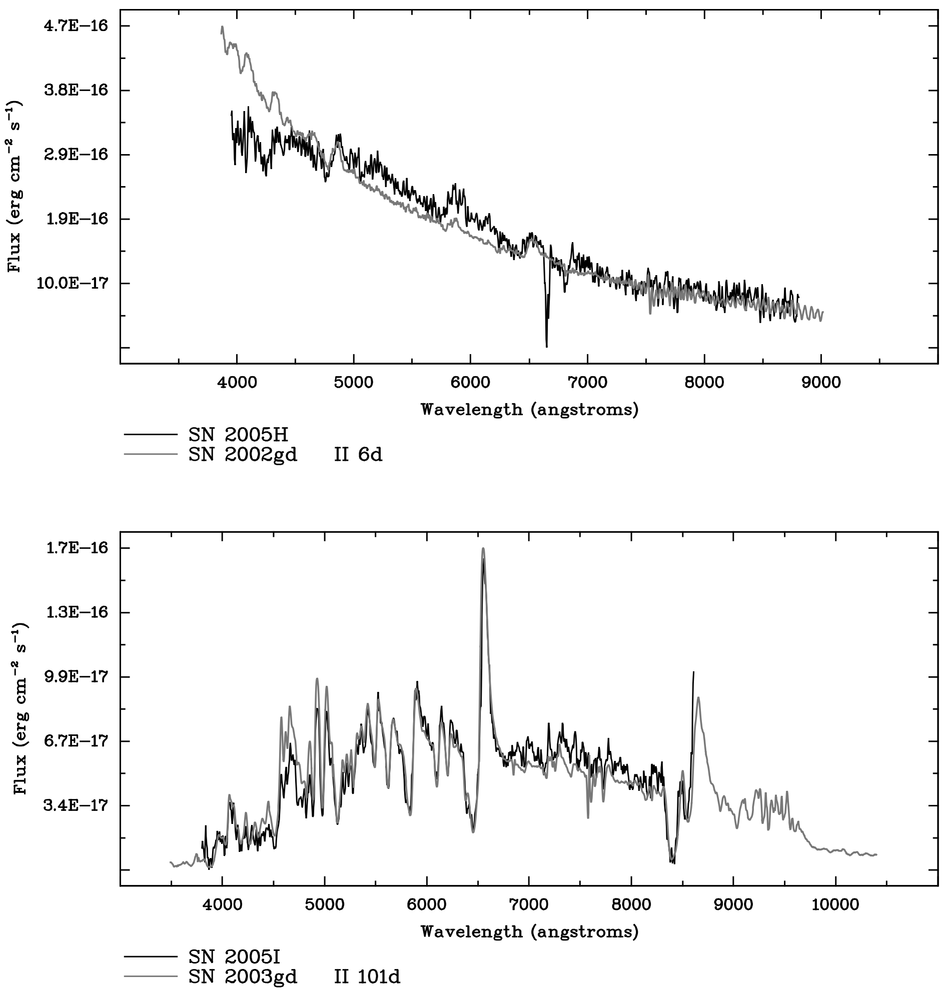


FIGURE 4.12– Same as Figure 4.1 for SN 2005H (top) and SN 2005I (bottom).

SN 2005H was found on Jan. 15.2 by Graham et al. (2005b) and classified as a young type-II supernova by Pastorello et al. (2005b). The spectrum is dominated by a blue continuum with overimposed P-Cyg profiles of H_β, Fe II and He I (Fig. 4.12 top). H_α is also present, with broad emission and a shallow absorption. The H_β and He I absorption minima are blueshifted by about 6600 and 6800 km s^{-1}, respectively. The best fitting template to this spectrum is that of the SN 2002gd, a low line velocity Ni-poor SN IIP 6 days after explosion (Pastorello et al. 2004). The featureless spectrum the peculiar line profiles lead, however, to a very low GoF = 1.01 (flat SED results in a lower value of GoF, see Section

3.1.4)

SN 2005I was discovered on Jan. 15.6 by Graham et al. (2005b). Pastorello et al. (2005b) classified it as a type-II supernova about 3 months after the explosion. The spectrum is characterised by a red continuum and narrow P-Cyg profiles of H_α, H_β, Ca II and Fe II lines (Fig. 4.12 bottom). The expansion velocities deduced from H_α and Fe II λ5018 lines are about 4900 and 2400 km s^{-1}, respectively. The best match is with the type-II SN 2003gd spectrum (ASA). Adopting for SN 2003gd the explosion epoch found by Hendry et al. (2005), the template is at an epoch of 101 days from the explosion, in good agreement with the phase estimate by Pastorello et al. (2005b).

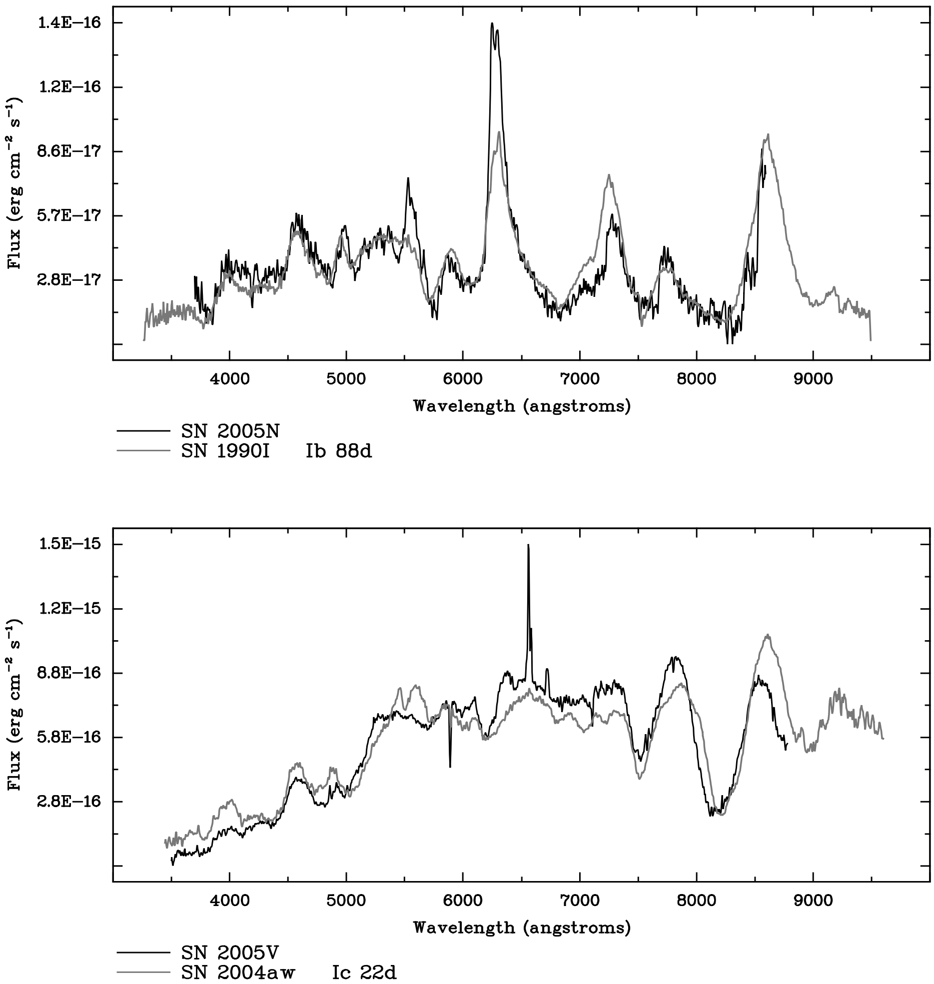


FIGURE 4.13– Same as Figure 4.1 for SN 2005N (top) and SN 2005V (bottom).

SN 2005N was found on Jan.19.6 by Puckett et al. (2005a) and classified as a type-Ib/c supernova in the nebular phase by Taubenberger et al. (2005a). The spectrum shows strong emission lines of Mg I], Na I D, [O I] and Ca II (Fig. 4.13 top). The best fit to this spectrum is with the type-Ib SN 1990I spectrum 88 days after maximum light (Elmhamdi et al. 2004), which, however, shows weaker [O I] emissions.

SN 2005V was found on Jan. 30.2 by Mattila et al. (2005) and classified as a type-Ib/c supernova by Taubenberger et al. (2005b). The spectrum shows P-Cyg profiles of Fe II, Na I D, O I and Ca II lines overimposed on a very red continuum (Fig. 4.13 bottom). A narrow H_α emission line, due to an underlying H II region, is present. The best match of this spectrum is with the type-Ic SN 2004aw 22 days after the maximum light (Taubenberger et al. 2006). The shape of the continuum and the presence of a deep Na I D absorption line (EW = 5.4Å) in the host galaxy restframe, suggest that SN 2005V is affected by heavy extinction (E(B-V) = 0.854 mag, Turatto et al. 2003). The absorption feature at 6200Å on the SN 2005V spectrum is most likely due to Si II (possibly blended with H_α). There is no evidence of He I lines.

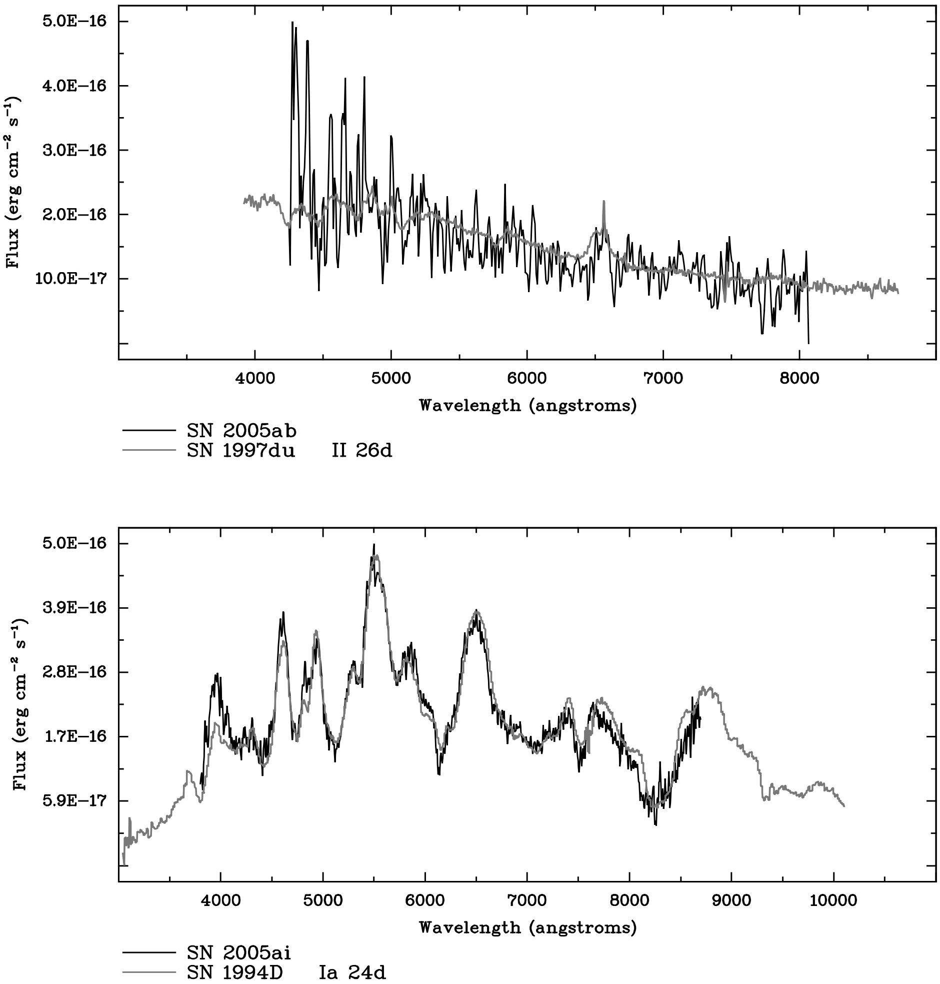


FIGURE 4.14– Same as Figure 4.1 for SN 2005ab (top) and SN 2005ai (bottom).

SN 2005ab was discovered on Feb. 5.6 by Nakano & Kadota (2005). Benetti & di Mille (2005) classified it as a type-II SN shortly after its explosion. On the very noisy spectrum (SNR $\approx$ 6) a relatively broad ($\sim$ 5000 km s^{-1}) H_α emission line is present (Fig. 4.14 top). The best fitting template spectrum is that of the type-II SN 1997du 26 days after its discovery (ASA, Patat 1997). The minimum of the H_β line absorption component in the SN 1997du spectrum is blueshifted by about 6900 km s^{-1}. Despite the low SNR, the absorptions at about 5770Å, 5110Å and 4950Å seem to be fitted by the SN 1997du absorptions of the Na I D 5892Å, Fe II 5169Å and Fe II 5110Å lines, therefore the phase of SN 2005ab could be more advanced than reported by Benetti & di Mille (2005).

SN 2005ai was found on Feb. 12.23 by Puckett et al. (2005b) and classified as a type-Ia supernova about one month past maximum light by Taubenberger et al. (2005d). The spectrum is that of a typical type-Ia SN (Fig. 4.14 bottom), and SN 1994D 24 days after the maximum light (Patat et al. 1996) yields the best match. This spectrum is similar to the spectrum of SN 2004go of the present sample.

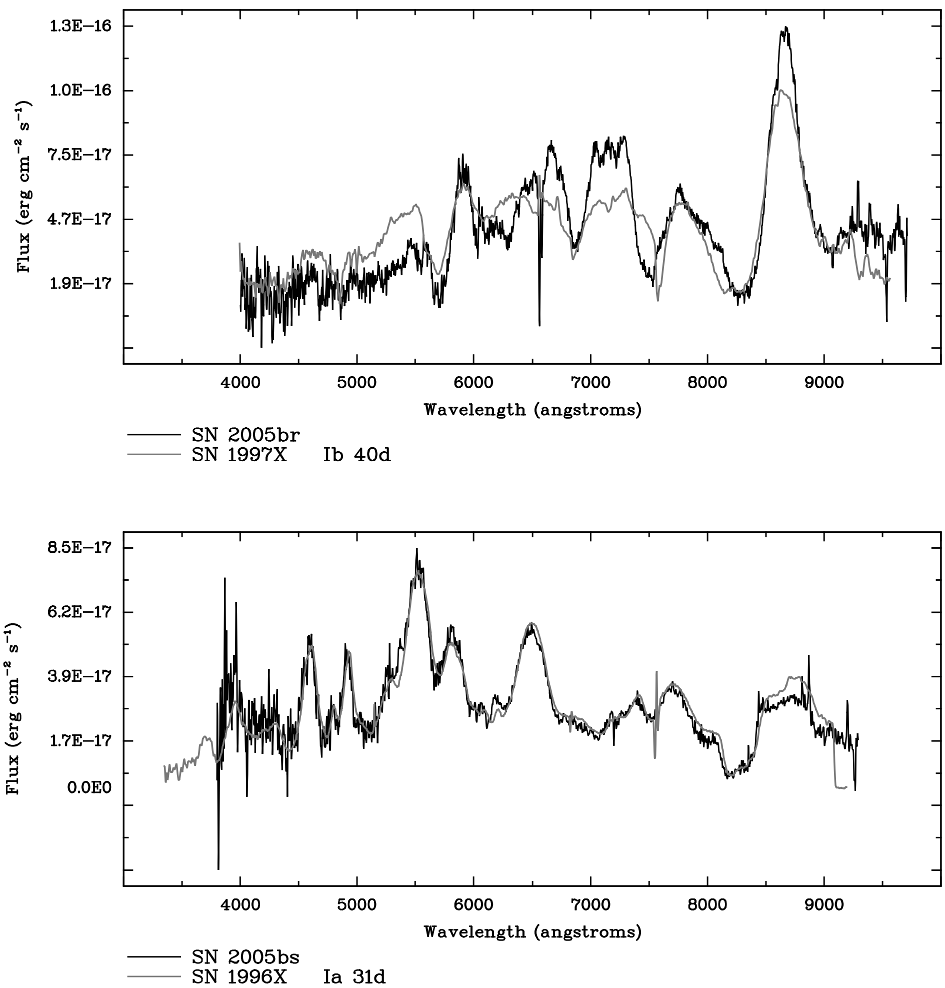
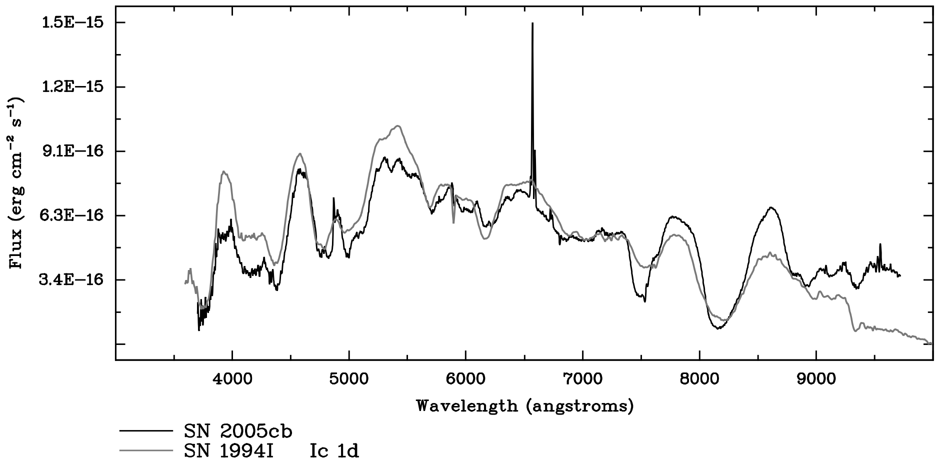


FIGURE 4.15– Same as Figure 4.1 for SN 2005br (top) and SN 2005bs (bottom).

SN 2005br was detected on Mar. 28.1 by Monard (2005a) and classified as a type-Ib supernova about 40 days past maximum by Turatto et al. (2005). The reddened spectrum shows features of He I (probably blended with Na I D), O I and Ca II (Fig. 4.15 top). Also, a rather strong (EW $\approx$ 2.6Å) interstellar Na I D absorption line is detected. The photospheric expansion velocity deduced from He I 5876Å is about 9000 km s^{-1}. The best fit to this spectrum is achieved with the type-Ib SN 1997X 40 days after discovery (ASA), However, the O I 7774Å line is shallower (probably contaminated by a telluric feature and less blueshifted) in 1997X. Also, a SN 1990U spectrum (ASA) provides a good fit. Adopting the B maximum epoch given by Piemonte (1996) for SN 1990U, the template spectrum phase is 48 days.

SN 2005bs was found on Apr. 19.1 by Monard (2005b), and Turatto et al. (2005) classified it as a type-Ia supernova. The spectrum (Fig. 4.15 bottom) resembles very well (GoF = 3.33) that of the type-Ia SN 1996X 31 day after the maximum light (Salvo et al. 2001), in agreement with the estimate by Turatto et al. (2005).



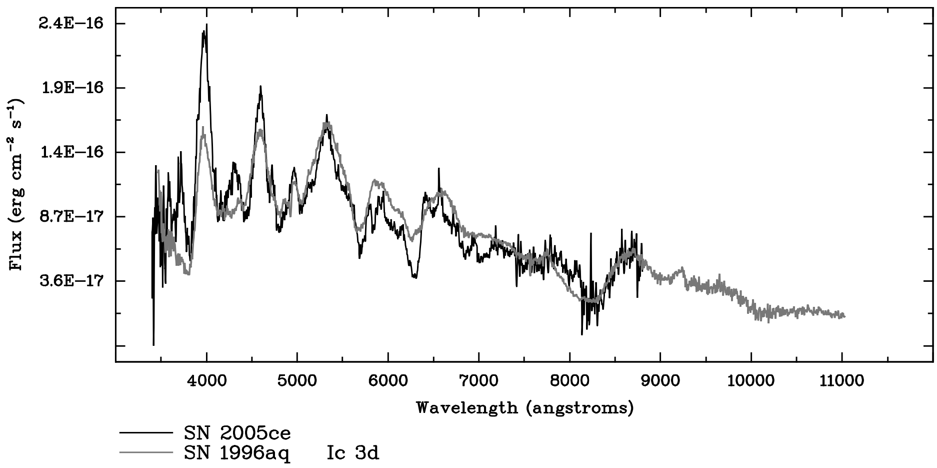


FIGURE 4.16– Same as Figure 4.1 for SN 2005cb (top) and SN 2005ce (bottom).

SN 2005cb was found on May 13.22 by Jacques et al. (2005) and classified as a type-Ib/c supernova at about 10 days after maximum by Turatto et al. (2005). P-Cyg profiles of Fe II, Na I D, Si II, O I and Ca II are present in the spectrum (Fig. 4.16 top). The expansion velocities deduced from the minima of Si II and O I features are about 9500 and 11000 km s^{-1}, respectively. The best fitting template is that of the type-Ic SN 1994I 1 day after B maximum light (Filippenko et al. 1995). SN 2005cb seems to be slightly redder than 1994I at maximum, and has a stronger O I with a higher line velocity.

SN 2005ce was found on May 28.5 by Pugh & Li (2005) and classified as a type-Ib/c supernova a few days after explosion by Stanishev et al. (2005a). The spectrum has a blue continuum with several P-Cyg profiles of Fe II, Ca II lines superimposed and moderately weak absorption lines at about 5700Å, 6496Å, 6850Å and 7060Å due to He I, with expansion velocities of about 8980, 8170, 9100 and 9140 km s^{-1}, respectively (Fig. 4.16 bottom). The best fit to this spectrum is provided by the type-Ic SN 1996aq 5 days after discovery (ASA). The spectrum is also similar to that of SN 1994I 10 days after B maximum, though in the SN 2005ce spectrum the O I feature is much weaker (if any). The deep absorption at about 6294Å is most likely due to H_α (probably blended with Si II and C II) as suggested by Branch et al. (2002); Elmhamdi et al. (2006) for many SNe Ib/c. This is supported by the identification of an absorption at about 4689Å with H_β. Usually the H_α line optical depth is small and no apparent H_β is detected, while in this case the H_α feature is strong and there is also some hint of H_β presence. With these identifications the photospheric expansion velocities derived from H_α and H_β lines are of about 12300 and 10600 km s^{-1}. Although the best fits found by our program are with type-Ic SNe, SN 2005ce is a rare and a very interesting example of an intermediate case between a Ib (with possibly some contamination of hydrogen) and Ic event.

SN 2005de was discovered on Aug. 2.28 by Lee et al. (2005) and classified as a type-Ia supernova one week before maximum by Wang & Baade (2005). Our spectrum of SN 2005de shows P-Cyg lines of Ca II, Fe II, S II and Si II (Fig. 4.17 top). The Ca II near-infrared triplet seems to be present with two components. This was noted by Wang & Baade (2005) who measured a velocity of about 20000 km s^{-1} for the bluer component, in agreement with our spectrum where the Ca II absorption minimum is blueshifted by 20200 km s^{-1}, taking 8579Å as the wavelength reference for the multiplet. Indeed, a high velocity feature is also present in the best fitting template spectrum of the type-Ia SN 2005cf 5 days before the maximum light (Garavini et al. 2007). Mazzali et al. (2005a) find that the presence of high-velocity features is very common, if not ubiquitous, in the early spectra of SNe Ia.

SN 2005dv was found on Sep. 4.8 by Dimai & Dainese (2005) and classified as a type-Ia supernova probably before maximum light by Leonard (2005). The minimum of the Si II λ6355 line is blue-shifted by about 12600 km s^{-1} suggesting that the phase of the spectrum is near-maximum (Fig. 4.17 bottom). The best fitting template is that of the type-Ia SN 2002bo at maximum light (Benetti et al. 2004b). The fit reproduces all spectral features rather well, though in the blue region the continuum of SN 2005dv spectrum is weaker, probably due to some reddening. This is confirmed by the presence of a Na I D absorption line (EW $\approx$ 2.3Å) in the rest frame of the host galaxy, as noted also by Leonard (2005).

SN 2005dz was found on Sep. 10 by Puckett et al. (2005c) and classified as a young type-II supernova by Stanishev et al. (2005b). The blue continuum of the spectrum is superimposed by broad and shallow P-Cyg profiles of H Balmer and He I λ5876 lines (Fig. 4.18 top). H_α is present mostly in emission. The expansion velocities derived from the H_α and H_β absorptions are about 12200 and 10600 km s^{-1}, respectively. The best fitting template spectrum is that of the type-II SN 2007T 4 days after discovery (Benetti et al. 2007b), although the expansion velocities of 2007T are smaller. The SN 2005dz spectrum is also similar to that of the type-II SN 2002gd 6 days after explosion (Pastorello et al. 2004).

SN 2005kl was discovered on Nov. 22 by Dimai & Migliardi (2005) and classified as a type-Ic supernova by Taubenberger et al. (2005c). P-Cyg profiles of O I, Ca II and also absorptions due to Si II and Fe II are present in the spectrum (Fig. 4.18 bottom). The red continuum suggests that the SN

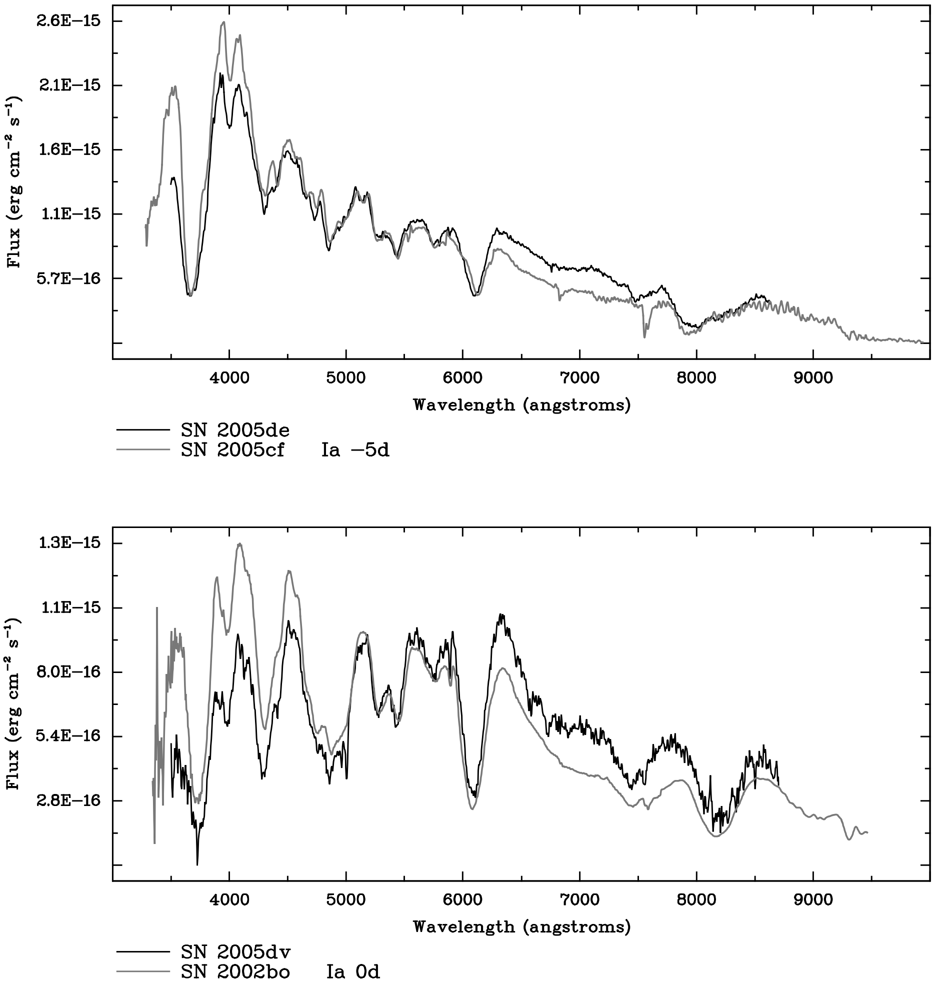


FIGURE 4.17– Same as Figure 4.1 for SN 2005de (top) and SN 2005dv (bottom).

is heavily extinguished. The best fitting template is the type-Ic SN 2004aw 4 days after B maximum (Taubenberger et al. 2006), which was also the case for SN 2004dk and 2004dn. The expansion velocity deduced from the Si II absorption is of about 10000 km s^{-1}. Here again, we have a large discrepancy in the SED of two spectra, which however did not obstacle GELATO to find the correct template, i.e. the template that has the same spectral features (with similar widths, at similar expansion velocities). This is reached through the spectra segmentation approach adopted in the design of the software.

4.1.3 Summary

The main goal of the European Supernova Collaboration (ESC) was to perform very detailed studies of nearby SNe Ia. It carried out extensive follow-up programs of a large SNe Ia sample. An important part of the ESC was an aggressive classification program with ToO observations of selected, newly discovered SNe, with the aim to single out candidates for the following intensive monitoring. In this context several tens of SN candidates were observed which did not meet the ESC requirements (see the introductory part

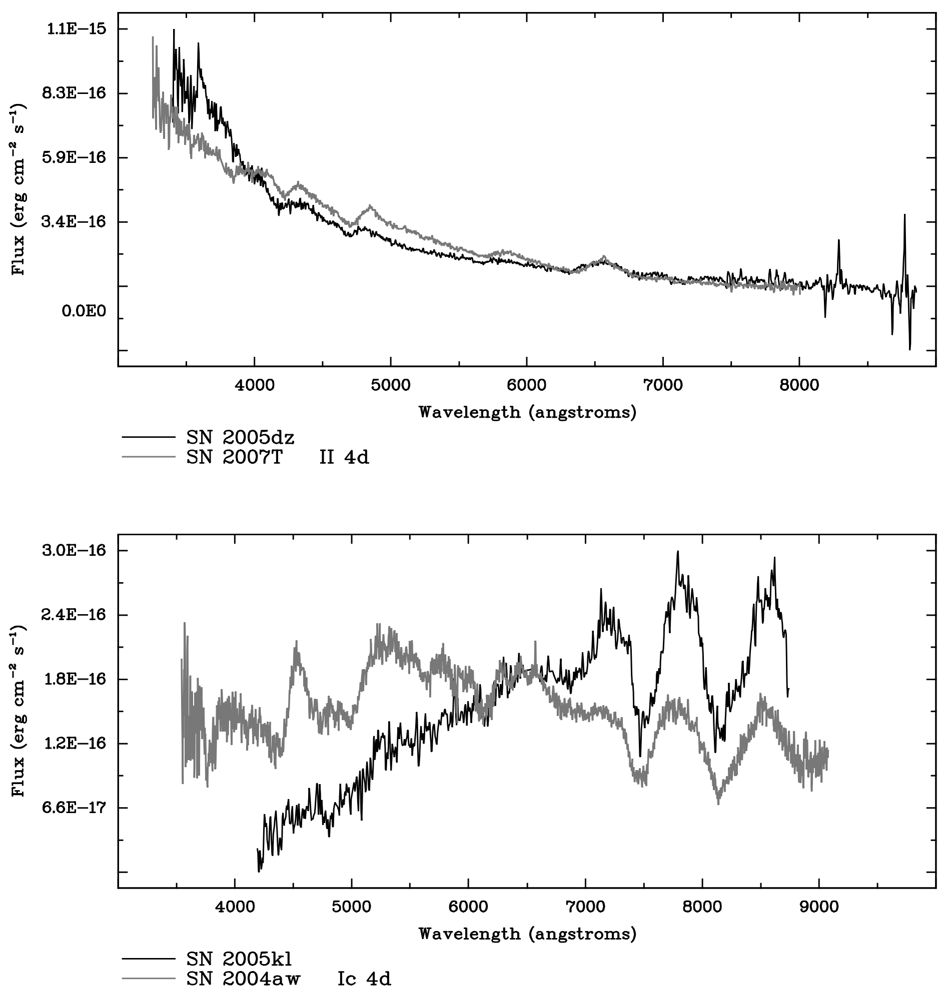


FIGURE 4.18– Same as Figure 4.1 for SN 2005dz (top) and SN 2005kl (bottom).

of this section) as to epoch of discovery and the SN type. In this section I have presented and discussed the spectra of these objects.

The types of the SNe of our sample, obtained with GELATO, are the same as those reported in the corresponding classification circulars. However, the classification of some SN have been refined. SN 2002hy appears to be an intermediate Ib/IIb event (instead of just Ib, see Figure 4.5). In fact, also its best matching template, SN 2001gh was mis-classified as a type-II SN. Another SN of our sample, SN 2002dg, might possibly be a transitional IIb event. So our sample includes 8 type-Ia, 13 type-Ib/c (with 2 possible cases of intermediate IIb evens) and 15 type-II SNe.

Using GELATO, we were able to date the SN spectra. In some cases the new spectral ages differ from those reported in the original circulars. The most important case was the type-Ia SN 2002cs. For this SN initially an age of 2 $\pm$ 2 days was given by the circular. Indeed, GELATO found a phase of -7 days, thus this SN might had become an important ESC target. For another object, type-Ia SN 2005de the GELATO phase was similar to the reported in the IAUC, but the program highlighted another interesting aspect.

In the above mentioned type-Ia SNe 2002cs and 2005de (both taken well before maximum), high-velocity features were, in fact, detected. This is confirmed by their best matches, SN 2004dt and 2005cf, respectively: which show high-velocity components in some lines and both objects belong to the HVG group (Benetti et al. 2005). Another case from our SN sample worth to mention, is that of the type-Ib SN 2004bs for which the age of ∼17-20 days after maximum is estimated. However, the high expansion velocities (~ 10000 km s^{-1}) derived for this object are inconsistent with such an advanced age, suggesting that the SN was probably at an earlier phase, which GELATO is not able to find because of the lack of the appropriate templates.

During this study GELATO proved to be a fast and reliable tool for SN classification. The SN types indicated by the software were in a good agreement with those provided by different expert SN observers. This fact demonstrates that the tool achieves the goal for which it has been conceived, that is the replication of an expert observer who (given a large amount of time) performs a detailed comparison of a given input spectrum to a large number of archive spectra. The subdivision of the spectra in bins, set in the design of GELATO, impels the program to give priority to the relative shape of the spectral features, but not to the form of the SED, hence reddening. See, for instance, the cases of SN 2003hg and 2005kl (Figures 4.5 4.18), where the little sensibility of GELATO to the SED of spectra is most obvious. The case of SN 2002cs shows the importance of having a reliable and objective classification tool and a complete SN template archive. Had such tools been available in 2002, SN 2002cs would have become an ESC target for detailed follow-up observations.

4.2 SN classification at Telescopio Nazionale Galileo*

In this section I present the material obtained during our SN classification program at Telescopio Nazionale Galileo†, called "Early time observations and rapid classification of Supernovae" (P.I. A.Harutyunyan).

In the last decades SN research have done big steps ahead in the understanding of SNe (see Chapter 1). Nowadays there are many ongoing projects, planned missions and high-z SN searches aimed either to probe the equation of state of dark energy observing SNe at high redshifts or to obtain the star formation history of the Universe using SN rates. It is clear however that all our advances in these topics are limited by our knowledge of the physical properties of SNe. Overcoming this limitation requires first of all to collect very high quality data through the monitoring of nearby SNe. The SN community and our team in particular is involved in a number of different large observational projects aiming to collect high quality data using different telescopes.

To succeed in such kind of observing campaigns it is crucial to achieve prompt, accurate classification of all new, nearby SNe. This kind of prompt characterisation of new objects allows a fast selection of the targets for the follow-up observations. This is one of the fields where the experience of our team can be best exploited. At the time we set up the SN classification at TNG, we already had SN spectra comparison procedures which, in combination with ASA, were well-suited for this purpose. With these

*The Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias

†http://www.tng.iac.es

tools, we could rapidly and reliably obtain from a single spectrum the classification of a SN, its phase relative to the maximum/explosion, the identification of possible peculiarities along with an estimate of the extinction. These information would then be used to activate and shape the strategy of a follow-up campaign.

The aim of our proposal for observations at TNG was the spectroscopic classification of nearby (v <5000 km s^{-1}) SNe likely to have been discovered well before maximum light. With this strategy we would also have a plenty of early-time spectra and would be able to probe the physical parameters of the outer part of the SN ejecta, which contains partially unburned matter that would give valuable informations on the progenitor system.

A total amount of 24 hours has been granted to this proposal for observations. The program was running during two periods (AOT 14, August 2006 - January 2007 and AOT 15, February 2007 - July 2007), 12 hours per period with the observations performed in ToO mode. After that the program was merged with our large program of SN observations at TNG (see Section 2.1).

4.2.1 The target selection, observations and data reduction

As soon as a an alert of a new SN discovery was received, a sequence of actions was performed. The distance of the object and its apparent magnitude were used to determine whether the SN was likely to fit the constraints of our program. Once an appropriate object was selected, a trigger of ToO observations was sent to the contact astronomer at TNG.

The spectra were obtained with DOLORES* mounted at the Nasmyth B focus of TNG. The instrument has both imaging and spectroscopy modes. During the program we used the spectroscopy mode to obtain low resolution spectra with 2 grisms: the LR-B (wavelength range 3000-8800Å, dispersion 2.8Å/pix, resolution 11Å for a 1" slit) and the LR-R (wavelength range 4470-10360Å, dispersion 2.9Å/pix, resolution 11Å for a 1" slit).

On average, a SN with a redshift of v<5000 km s^{-1} will be around magnitude 15.5 - 17 (if phase ≤-7d). Mean exposure times of ~ 30-45min were sufficient for reaching an average SNR of ~50, thus the typical time required for a ToO trigger was about 1 hour (including overheads). A part of the ToO time has been lost due to weather or technical problems and we obtained for the two periods a total number of 13 SN classifications.

This sample of 13 spectra is presented in Table 4.3, where the basic information on observations, grisms and spectra is listed. The last column of the table contains the references of the discovery and the classification circulars (CBET). The image reduction, spectra extraction and calibration checks are performed using standard IRAF subroutines, as described in Section 4.1.

4.2.2 Results and description of individual spectra

For the 13 spectra obtained during our program, detailed information about the type and age of the objects were determined, their expansion velocities and reddening were estimated and the presence of eventual peculiarities was checked. For 2 of them, SN 2006gy and 2006jc, we decided to perform dedicated

*http://www.tng.iac.es/instruments/lrs/

TABLE 4.3– The sample of spectra obtained during the SN classification program at TNG.

SN	Discovery	Acquisition	Grism	Spectral range	Resolution[1]	Reference
	DD/MM/YY	DD/MM/YY		Å	Å	CBET
2006en	27/08/06	28/08/06	LR-B, LR-R	3600 - 9000	12	606, 608
2006gy	18/09/06	26/09/06	LR-B, LR-R	3300 - 9100	12	644, 647, 648, 695
2006jc	09/10/06	12/10/06	LR-B, LR-R	3400 - 10000	13	666, 672, 674, 677
2007B	05/01/07	08/01/07	LR-B	3200 - 7900	12	797, 799
2007K	16/01/07	17/01/07	LR-B	3500 - 7900	20	812, 813
2007O	21/01/07	23/01/07	LR-B	3300 - 7800	12	818
2007R	26/01/07	31/01/07	LR-B	3300 - 7800	18	823, 826
2007T	03/02/07	07/02/07	LR-B	3300 - 8000	18	833, 837
2007av	20/03/07	22/03/07	LR-B	3300 - 8000	14	901, 903
2007bg	16/04/07	21/04/07	LR-B, LR-R	3500 - 10000	20	927, 948
2007bw	18/04/07	20/05/07	LR-B, LR-R	3500 - 8800	13	941
2007cs	24/06/07	28/06/07	LR-B, LR-R	4300 - 9400	13	986, 987
2007fo	09/07/07	16/07/07	LR-B	3800 - 7400	12	997, 1001

Note:
[1] measured on the FWHM of the night sky lines

TABLE 4.4– The results of comparison of the TNG spectra with GELATO. Best match template phases are relative to the B-maximum epoch for type-Ia and Ib/c SNe and to explosion epoch for type-II SNe.

SN	Type	Best match SN template	GoF	Template phase (days)*	Template spectrum reference
2006en	Ia	2003du	3.1	4	Stanishev et al. (2007)
2006gy	IIn	2000eo	1.0	10	ASA
2006jc	Ibpec	2000er	1.0	7	ASA
2007B	Ia	1994D	3.1	-4	Patat et al. (1996)
2007K	IIn	2003G	1.9	15	ASA
2007O	Ia	2003du	4.1	-2	Stanishev et al. (2007)
2007R	Ia	1996X	3.7	-2	Salvo et al. (2001)
2007T	II	1995ad	1.3	12	Pastorello (2003)
2007av	II	2005ay	1.5	9	Bufano et al. (2007)
2007bg	Ic/II	1998bw	1.2	19	ASA
2007bw	IIn	1998S	1.2	12	ASA
2007cs	Ia	1997bp	1.1	19	ASA
2007fo	Ib	1997dc	1.4	21	Matheson et al. (2001)

Note:
* the best match template phases for type-Ia SNe are relative to B-maximum and for type-II SNe to the explosion epoch. The phase for SN 1997dc is imprecise (see Matheson et al. 2001). The phases for SN 2000eo and 2003G are relative to the discovery date.

follow-up observations. These two objects turned out to be the most exciting SNe discovered in the last decade.

GELATO was used for classification of the spectra in "real-time mode", i.e. to obtain the classification of entirely new, unknown SNe. Immediately after the classifications, an electronic telegram with the classification and preliminary analysis results was sent to the Central Bureau of Astronomical Telegrams (CBAT). A total of 11 classification telegrams has been published. For the two remaining SNe the classifications performed by other groups anticipated ours, thus we did not send telegrams for them.

The results obtained using GELATO are summarised in Table 4.4, listing for each object the best template, the phase and the GoF. Figures 4.19 - 4.29 show the plots of the spectra of our sample together with their best fitting templates. In the figures, the templates are scaled in flux to match the input spectra. The spectra are shown in the parent galaxy restframe and are not corrected for extinction (except for the SN 2006gy case). Below I present a short discussion on individual objects.

As mentioned above, two of the objects observed during this program received further observations. Both, SN 2006gy and SN 2006jc, appeared to be extraordinary events and thanks to our fast classification program we were able to reveal their peculiar nature and timely trigger coordinated follow-up observations at different telescopes. Additionally, the spectra obtained in this program were important since they were the earliest spectra of the respective objects. In this section I present detailed descriptions of these SN providing information about the results obtained for these SNe after their follow-ups.

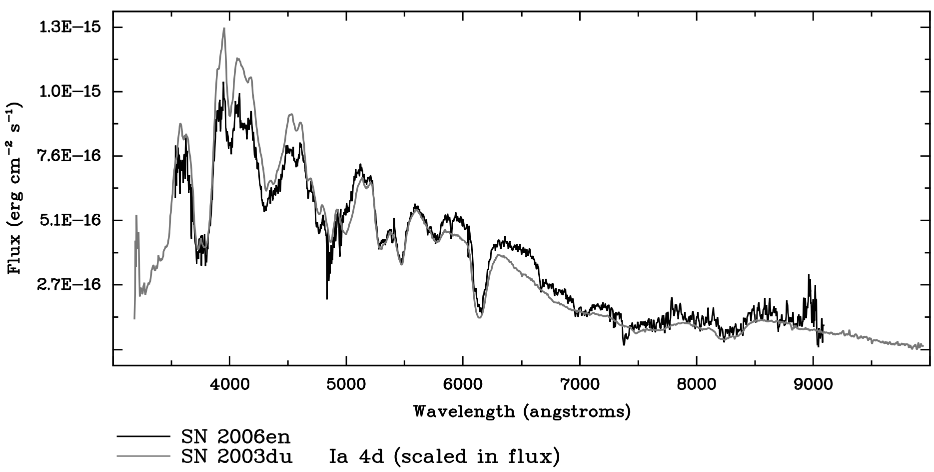


FIGURE 4.19– The comparison of SN 2006en spectrum with its best fitting template. Hereafter, the spectra are in the parent galaxy restframe and not corrected for extinction. The black lines are the spectra of the sample, while the gray ones display template spectra.

SN 2006en was found on Aug. 27.15 by Puckett & Peoples (2006) and classified as a type-Ia supernova around maximum light by Elias-Rosa et al. (2006a). The expansion velocity deduced from the Si II 6355Å minimum is 10200 km s^{-1}. An interstellar Na I D absorption feature is visible in the host galaxy rest frame (see Figure 4.19) with EW of about 2Å, suggesting a reddening E(B-V) > 0.3 mag (Turatto et al. 2003). Taking into account the apparent magnitudes reported by Puckett & Peoples (2006), it would appear that SN 2006en is an extremely luminous object ($M_{unfiltered} \sim$ -19.8), but this seems inconsistent with our spectrum and with the normal expansion velocity derived from it. The best match found by GELATO is the type-Ia SN 2003du spectrum 4 days after the maximum (Stanishev et al. 2007).

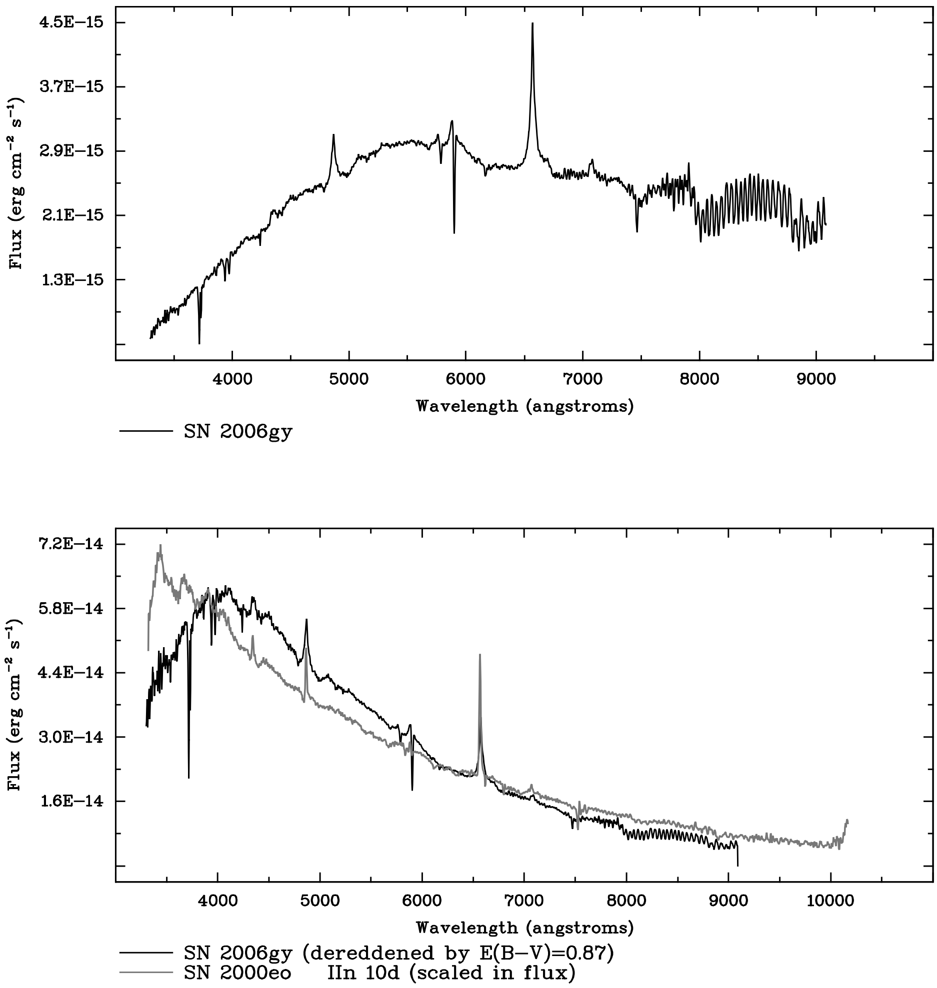


FIGURE 4.20– Top: the spectrum of SN 2006gy obtained on 26/09/06 (top). Bottom: the same spectrum dereddened by E(B-V)=0.87 (black line) together with its best fitting template of SN 2000eo (gray line). The spectra are in the parent galaxy restframe.

SN 2006gy was discovered at about 2” west and 0.4” north of the center of NGC 1260, on Sep. 18.30 by Quimby (2006) and classified as a type-II supernova shortly after explosion by Harutyunyan et al. (2006). The early analysis of the spectrum (see Figure 4.20 top panel), heavily contaminated by the parent galaxy, showed that it is dominated by a relatively red continuum with overimposed H_α and H_β lines. H_α is present with a complex profile consisting of three emission components: a narrow unresolved one, an intermediate (FWHM about 2500 km s^{-1}) one, and a broad one (FWHM about 9500 km s^{-1}). The He I 5876Å emission is also present. An interstellar Na I D absorption feature is visible in the host galaxy rest frame with an equivalent width of about 5.5Å suggesting a reddening E(B-V) $\approx$ 0.87 mag (Turatto et al. 2003). When corrected for reddening (Figure 4.20 bottom panel), the spectrum is similar to that of type-IIn SN 2000eo 10 days after discovery (ASA).

Prieto et al. (2006a) obtained another spectrum almost simultaneously to our one and suggested that the object was instead an active galactic nucleus. They supported this with the fact that the Balmer lines were symmetric, which is unusual for SNe at early phases. In addition, the position of the object was consistent with the center of the host galaxy, and, after correcting for the extinction (2 mag), the absolute magnitude of SN 2006gy resulted -22. Further, Foley et al. (2006) reported the 1" offset (seen using adaptive optics) of the SN position from the nucleus of the galaxy. This, along with the spectrum obtained almost one month after ours confirmed that SN 2006gy is a type-IIn event.

While the spectroscopic display was already seen also in other type-IIn events, the extraordinary luminosity of SN 2006gy attracted the attention of SN researchers. Several groups, among which also the Padova SN group, started spectroscopic and photometric follow-up observations of this object. With a V-band peak absolute magnitude of about -22, SN 2006gy is probably the brightest SN ever recorded. Its slow raise to maximum of $\sim$ 70 days and the total radiated energy of $\sim 10^{51}$ erg in first two months (Ofek et al. 2007; Smith et al. 2007) make it an extraordinary event. Figure 4.21 shows the comparison of the absolute R-band light curve of SN 2006gy with those of other SNe (from Smith et al. 2007).

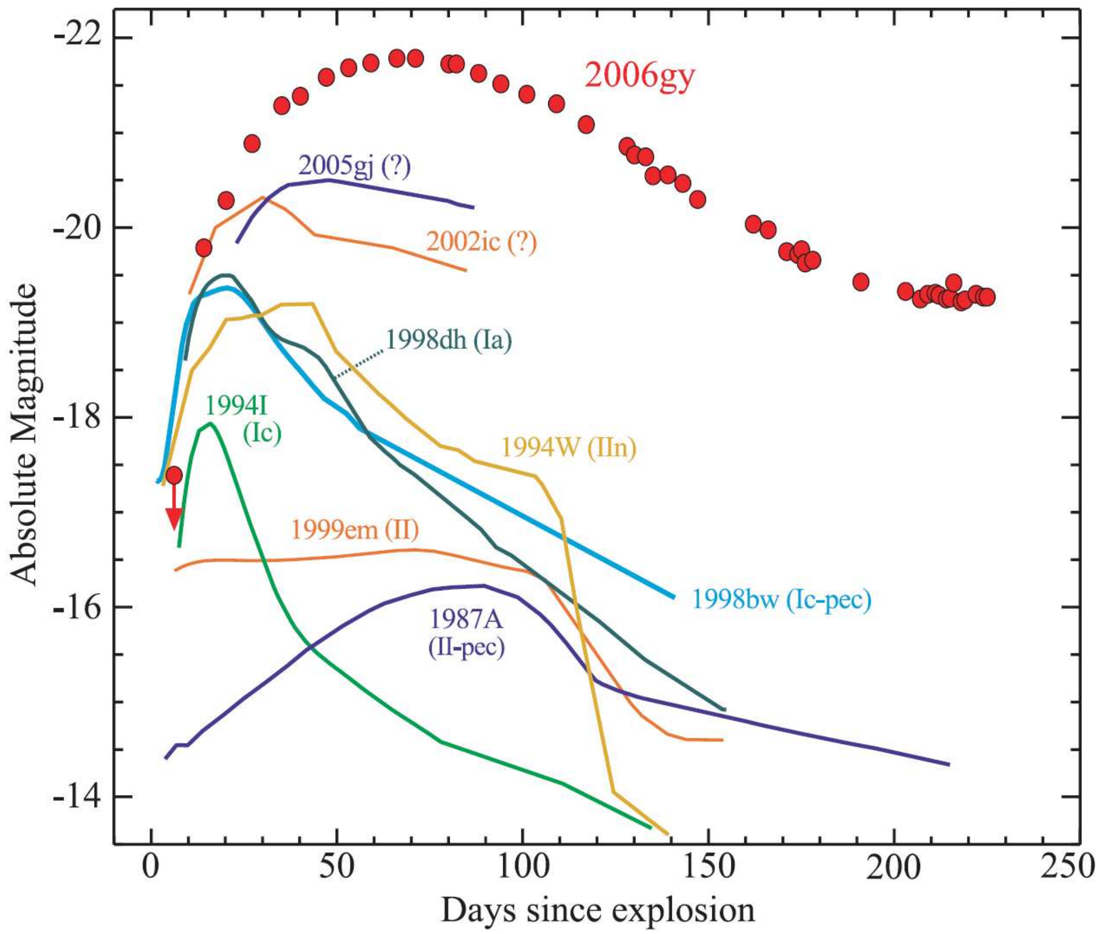


FIGURE 4.21– Comparison of the absolute R-band light curve of SN 2006gy with those of other SNe (from Smith et al. 2007).

All the various hypothesis for the progenitor star agree that the SN is caused by an explosion of a massive or supermassive star in a dense hydrogen-rich medium. In fact, the scenario of a white dwarf exploding inside a hydrogen envelope (so called “type IIa” event) proposed by Ofek et al. (2007) is ruled out by the observational evidences showing the presence of hydrogen in the progenitor. The fact that only weak X-ray emission from SN 2006gy is detected by Chandra (Smith et al. 2007) implies a high density of the circumstellar medium (CSM) to absorb almost entirely the X-ray emission caused by the ionisation of CSM (because of the ejecta-CSM collision). Pair-instability processes (Smith et al. 2007; Woosley et al. 2007) seem to be the explanation of the huge mass-loss rates creating the dense material around the star prior to the SN explosion.

While several progenitor scenarios (see Ofek et al. 2007; Smith et al. 2007; Smith & McCray 2007; Woosley et al. 2007) have been proposed to explain the behavior of the SN, it is still not clear what precisely powers the enormous luminosity and the amount of radiated energy. In particular, it has been proposed that SN 2006gy could be: a pair-instability SN explosion, with an enormous amount ($22M_{\odot}$) of ejected Ni and the star’s core entirely destroyed (Smith et al. 2007); a core-collapse of a massive star whose ejecta hit a massive ($10M_{\odot}$), large (160AU), opaque circumstellar envelope (Smith & McCray 2007); the collision of shells of material that has been released during a pulsational pair-instability activity of a massive star (Woosley et al. 2007).

As said above, our group has done observations of SN 2006gy starting from the early phases. In fact, the spectrum shown in Figure 4.20 obtained during our classification program is the earliest spectrum of this object ever taken. Also, we performed observations of the SN at the late phases and these data will be published soon (Agnoletto et al., 2008, in preparation). Using the collected data, Agnoletto et al. (2008) show that the pair-instability SN explosion ejecting $22M_{\odot}$ of Ni may possibly be ruled out.

While the investigations of this extraordinary object already gave the first evidences of unprecedented progenitor configurations and explosion mechanisms, further studies are required to understand the real nature of SN 2006gy.

SN 2006jc was discovered in UGC 4904 on 2006 Oct. 9.75 at magnitude 13.8 by Nakano et al. (2006). Crotts et al. (2006); Fesen et al. (2006a) reported that it was likely a type-Ib SN, though Fesen et al. (2006b) further reported that the spectrum contained features characteristic of a type-Ia SN. Benetti et al. (2006a) reported that our spectrum (Figure 4.22), obtained almost simultaneously (on Oct. 12.23) to those of Fesen et al. (2006a;b), is that of a peculiar type-Ib SN, having a spectrum similar to those of SN 1999cq and 2002ao. The spectrum is characterised by strong He I emission lines at 5876, 6678, 7065Å. A later spectrum obtained by Modjaz et al. (2006) confirms the peculiar nature of the SN together with narrow emission lines due to He I. The best match to the classification spectrum of SN 2006jc was found using GELATO. The best template was the peculiar type-Ib SN 2000er spectrum 7 days after discovery (ASA). The low value of GoF = 1.0 suggests that the fit quality is low and the spectra are not very similar. A visual inspection of the fit shows that main similarities reside on the narrow He I features, while SN 2000er is different in the broad ones, neither are the SED of two spectra similar. This reveals that SN 2006jc is peculiar and our templates archive lacks spectra that are similar to the SN 2006jc one.

We started the follow-up observations of this interesting object using various telescopes, and the detailed analyses of the early SN data were performed and published by Pastorello et al. (2007b). An op-

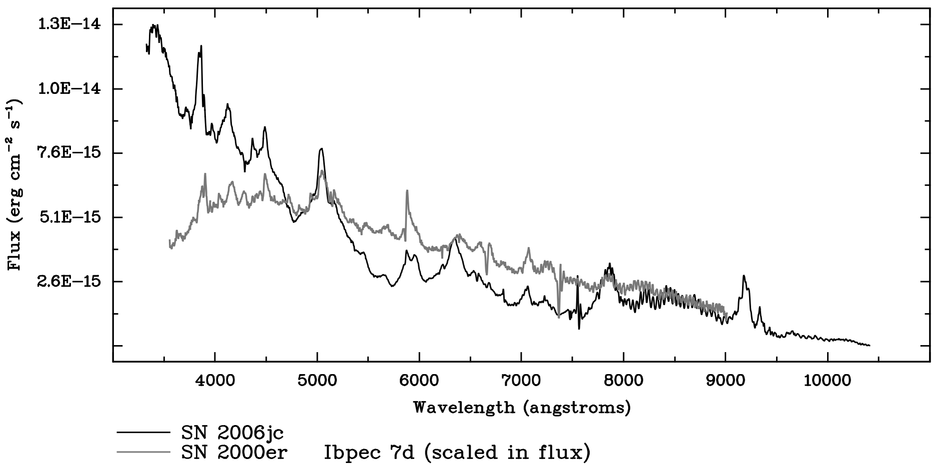


FIGURE 4.22– The classification spectrum of SN 2006jc (black line) obtained during our classification program at TNG overplotted with the best match from our templates database, the peculiar type-Ib SN 2000er spectrum 7 days after discovery (gray line). The spectra are in the parent galaxy restframe.

tical transient, reported to the the Central Bureau for Astronomical Telegrams (CBAT) in 2004, appeared to be spatially coincident with the new SN. Pastorello et al. (2007b) showed that the transient (called UGC 4904-V1) and SN 2006jc were indeed spatially coincident to within the uncertainties.

The study of dataset revealed that the SN was discovered a few days past maximum, but its brightness was still comparable with that of the most luminous type Ic supernovae, namely $M_R <$ -18.3 mag. Figure 4.23 displays the UBVRI light curves of SN 2006jc together with the comparisons with those of other 2 similar events (SN 1999cq and SN 2002ao) and other hydrogen-deficient core-collapse SNe (from Pastorello et al. 2007b). In the spectra, broad emission lines commonly observed in type Ic supernovae are detected, although with an atypical profile. In addition, prominent and relatively narrow (FWHM $\approx$ 2200 km s^{-1}) He I emission lines are observed, hence the classification of SN 2006jc as a peculiar type Ib event. See Figure 4.24 for the spectral evolution and line identification (Pastorello et al. 2007b)

The presence of narrower lines superimposed on broad spectral features and the strong X-ray emission detected from SN 2006jc (Immler et al. 2006) are signatures of presence of CSM. The presence of prominent He I lines and the lack of conspicuous hydrogen features suggest a helium-rich composition for the CSM, while the abundance of hydrogen must be low. There is no evidence of broad helium components, suggesting that the progenitor of SN 2006jc had entirely lost its helium envelope and was a carbon-oxygen Wolf–Rayet star. Severe mass loss is necessary to remove the outer hydrogen and helium layers, and to expose the massive carbon-oxygen core.

The 2004 outburst of UGC 4904-V1 reached a peak magnitude of $M_R \approx$ -14.1, and a Luminous Blue Variable (LBV) eruption (like η Carinae Davidson & Humphreys 1997) might be one of the explanations of the event, since the magnitude of the 2004 outburst was similar to that of a typical LBV flash. However, an LBV scenario raises two problems: it is inconsistent with current stellar evolutionary theory, which predicts that massive stars do not undergo core-collapse in the LBV stage, and also that the subsequent

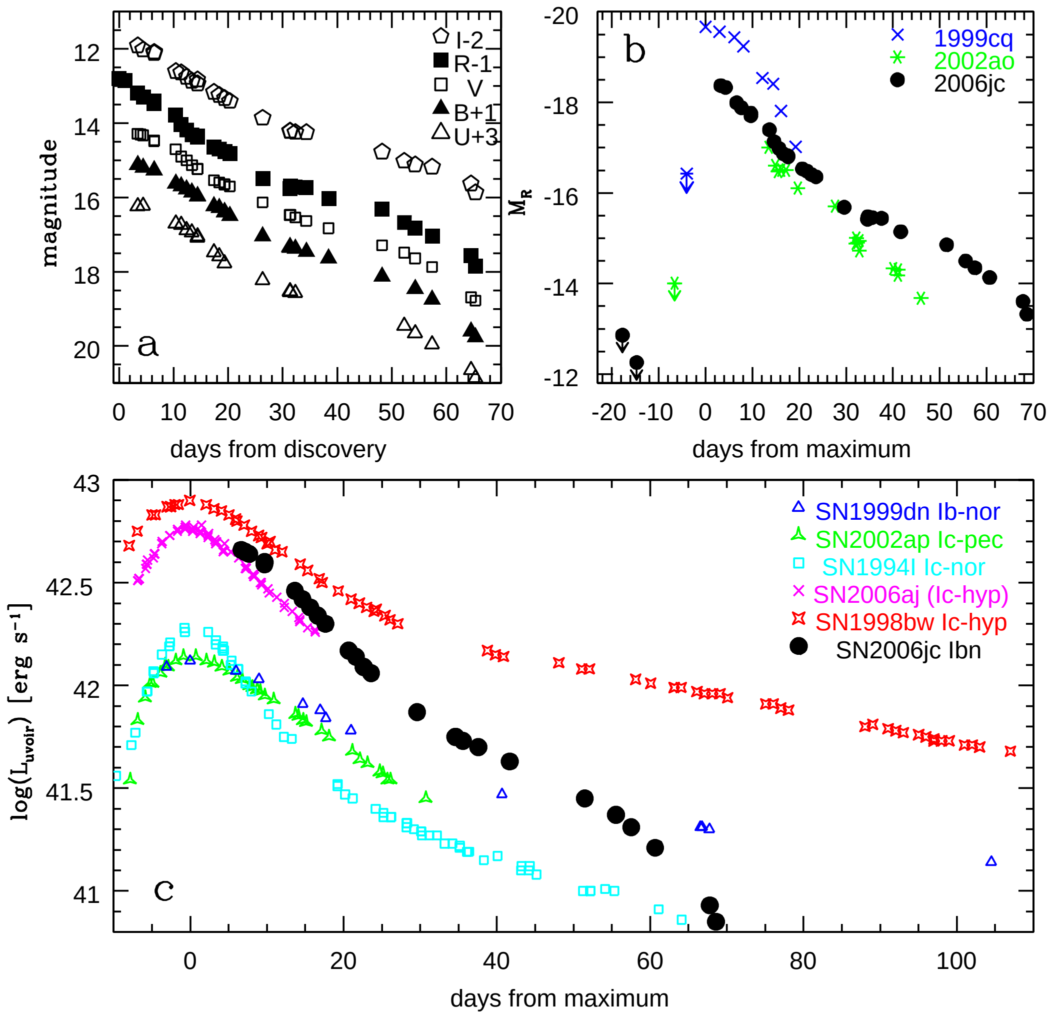


FIGURE 4.23– UBVRI light curves of SN 2006jc (a). The R-band absolute light curve of SN 2006jc compared with unfiltered light curves of two similar interacting type Ib events: SN 1999cq and SN 2002ao (b). Comparison between the quasi-bolometric (uvoir) light curve of SN 2006jc and those of a sample of hydrogen-deficient core-collapse supernovae (from Pastorello et al. 2007b).

Wolf–Rayet star should have a lifetime of more than 200000 years (Heger et al. 2003; Eldridge & Tout 2004). Additionally, an LBV that has undergone outbursts should still have hydrogen- and helium-rich atmosphere (Davidson & Humphreys 1997). The progenitor configuration of SN 2006jc was different, because prominent hydrogen lines were not detected in early supernova spectra (Pastorello et al. 2007b).

As an alternative to the single star scenario, Pastorello et al. (2007b) propose a massive binary system with two stars entering the final, violent, stages of their evolution. One of the components could have undergone a classical LBV outburst in 2004, while the companion was an evolved Wolf–Rayet star that collapsed to give SN 2006jc. The interaction of the ejecta within a complex, circumstellar environment shaped by the strong stellar winds of the massive stars could explain the numerous gas shells detected in the spectra. It has recently been suggested that η Carinae has a hot companion which is a nitrogen-rich

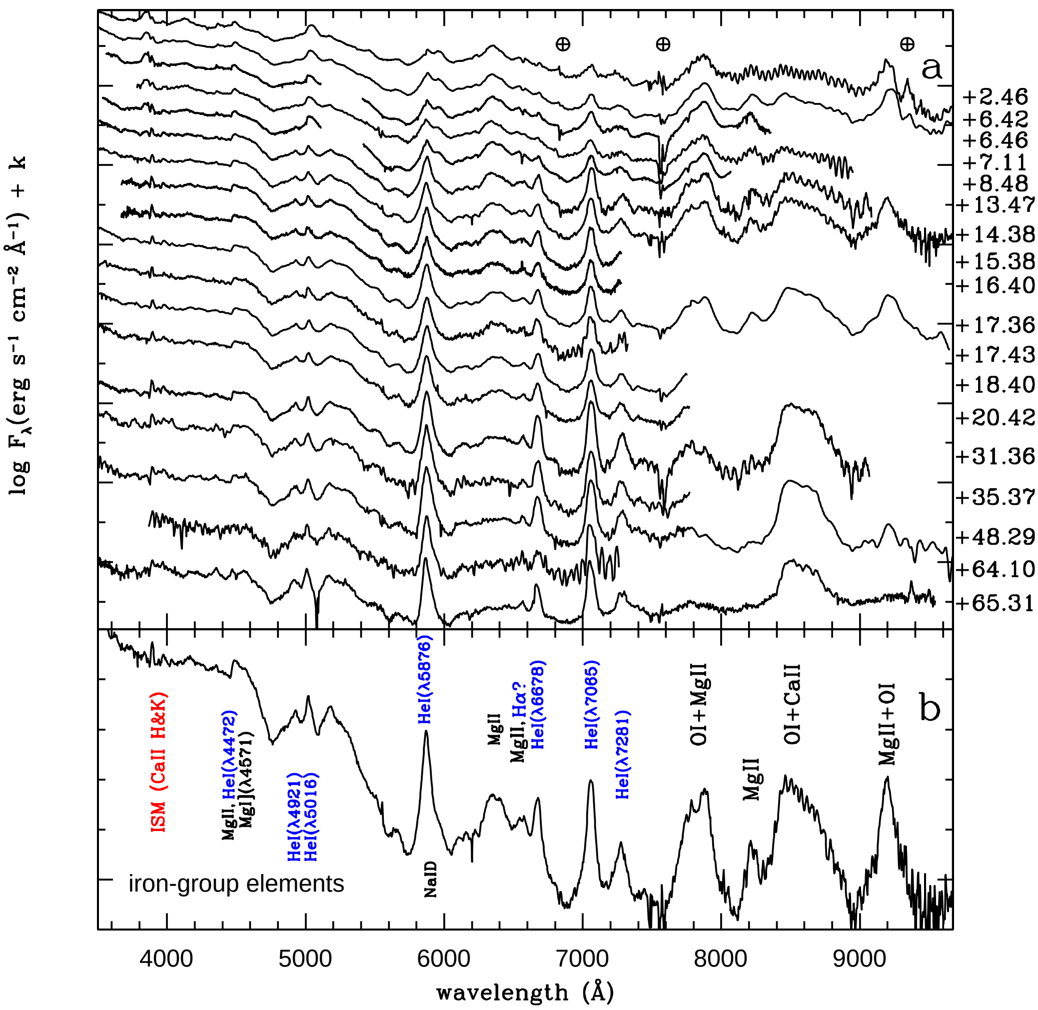


FIGURE 4.24– Spectra evolution of SN 2006jc (a) and identification of the main features in the spectrum at +14.38 days (b). All spectra have been shifted to the host galaxy rest wavelength (from Pastorello et al. 2007b).

late O-type or Wolf–Rayet star (Iping et al. 2005). A similar scenario was proposed for HD 5980, an LBV + Wolf–Rayet star binary in the Small Magellanic Cloud (Koenigsberger et al. 2002). In neither of these cases is the Wolf–Rayet star a WC or WO, as it is still nitrogen- and helium-rich, but a more evolved system cannot be excluded Pastorello et al. (2007b). Further observational and theoretical studies are required to determine which scenario is the more likely.

SN 2007B was discovered on Jan. 5.38 by Nakano & Itagaki (2007) and classified as a type-Ia SN near maximum light by Benetti et al. (2007a) (see Figure 4.25, top panel). The expansion velocity derived from the Si II 6355Å minimum is about 11800 km s^{-1}. The best fitting template is the type-Ia SN 1994D 4 days before B-maximum (Patat et al. 1996).

SN 2007K was found on Jan. 16.40 by Madison & Li (2007a) and classified as a type-IIn supernova by Harutyunyan et al. (2007c). The spectrum (see Figure 4.25, bottom panel) has a blue continuum,

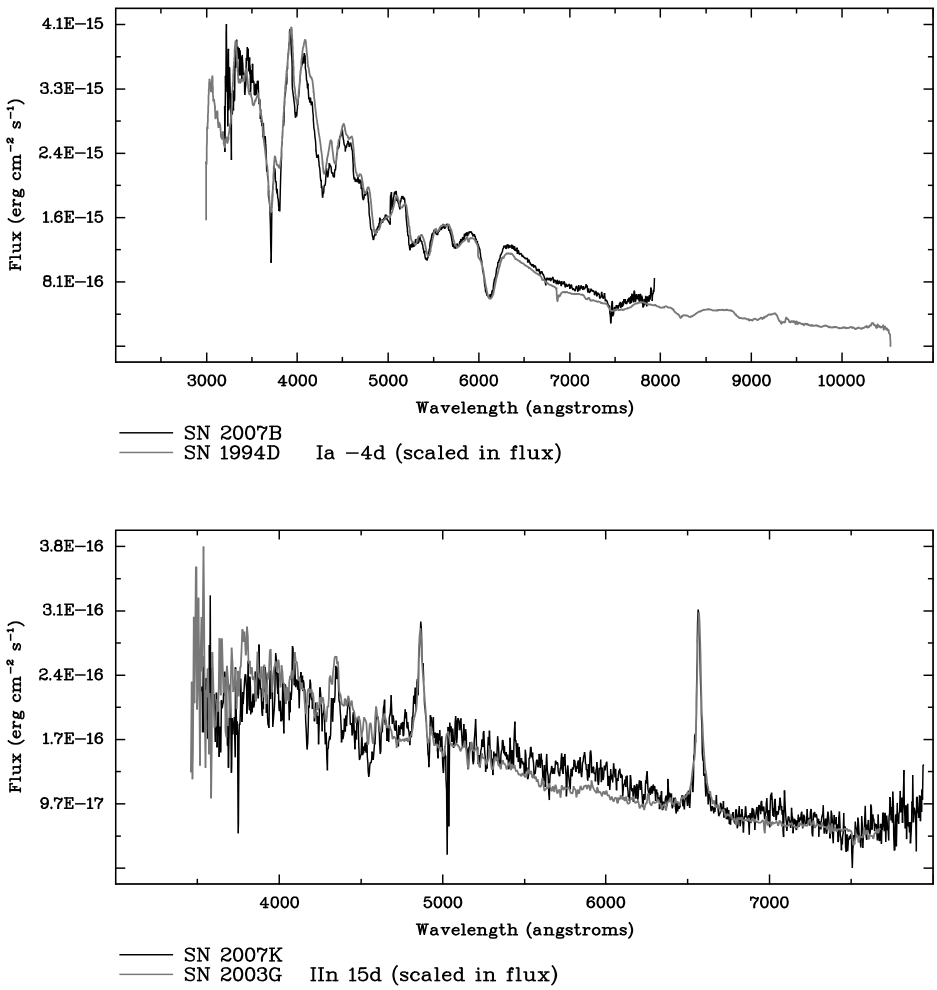


FIGURE 4.25– Same as Figure 4.19 for SN 2007B (top) and SN 2007K (bottom).

superimposed by emissions due to H_α, H_β and H_γ lines. H_α shows a composite profile consisting of a narrow (unresolved) component superimposed to a broader (FWHM about 3100 km s^{-1}) component. The best match is with the type-IIn SN 2003G spectrum 15 days after discovery (ASA). Also the spectrum of type-IIn SN 1995G 2 days after discovery (Pastorello et al. 2002) provides a good fit (GoF = 1.7).

SN 2007O was discovered on Feb. 21.60 by Lee & Li (2007). Silverman et al. (2007) classified it as a type-Ia SN 1 $\pm$ 2 days past maximum brightness, in agreement with our subsequent classification and phase estimate (Harutyunyan et al. 2007b). The spectrum (see Figure 4.26, top panel) closely resembles (GoF = 4.1) that of SN 2003du 2 days before maximum (Stanishev et al. 2007). The expansion velocity derived from the Si II 6355Å line minimum is about 9900 km s^{-1}.

SN 2007R was found on Jan 26.10 by Puckett et al. (2007) and classified as type-Ia supernova near maximum light by Harutyunyan et al. (2007d) (see Figure 4.26, bottom panel). The expansion velocity, deduced from the Si II 6355Å absorption feature in the spectrum, is about 11600 km s^{-1}. The best match is the type-Ia SN 1996X 2 days before maximum Salvo et al. (2001).

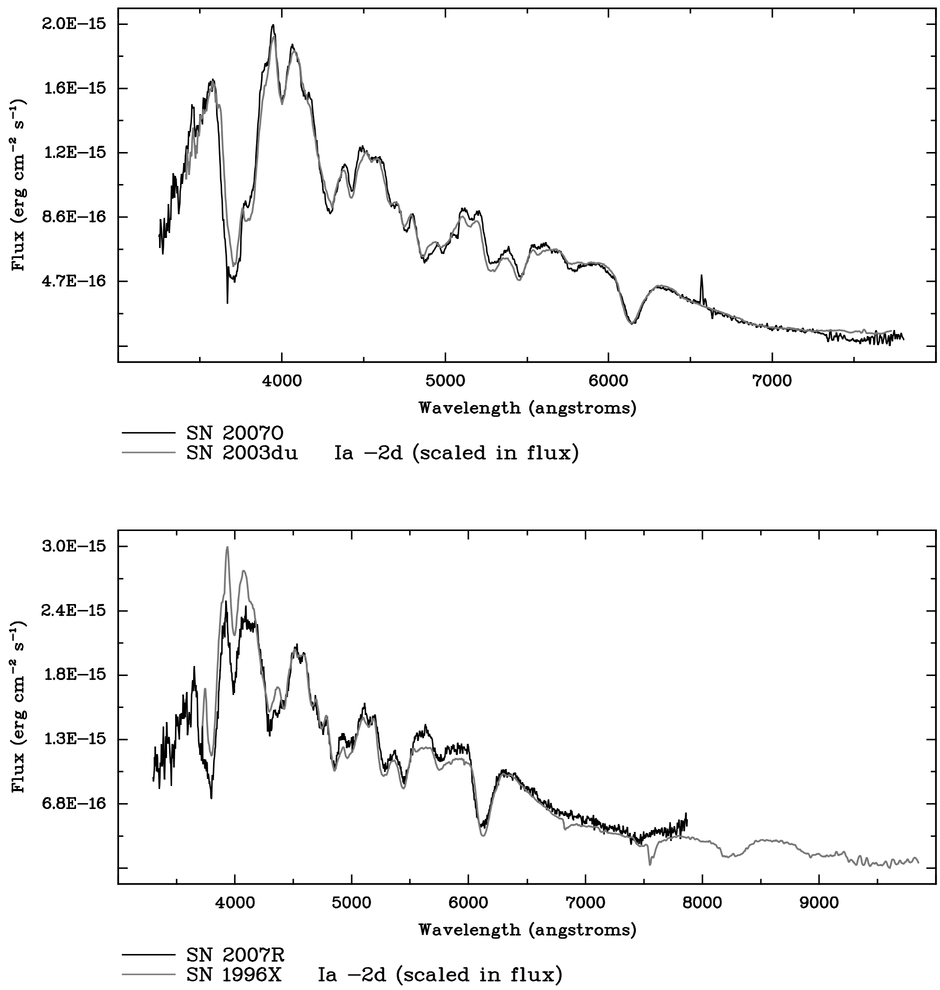


FIGURE 4.26– Same as Figure 4.19 for SN 2007O (top) and SN 2007R (bottom).

SN 2007T was discovered on Feb. 3.57 by Madison & Li (2007b) and classified as a type-II supernova shortly after explosion by Benetti et al. (2007c). The spectrum (see Figure 4.27, top panel) consists of a blue continuum (T_{bb} about 12700 K) superimposed by P-Cyg profiles of H_β, H_γ and He I 5875 lines. H_α is present, mostly with a broad (FWHM about 10400 km s^{-1}) emission profile. The expansion velocity deduced from the H_β minimum is about 9600 km s^{-1}. The best fit to this spectrum found by GELATO is provided by the type-IIP SN 1995ad 12 days after explosion (Pastorello 2003).

SN 2007av was found on Mar. 20.83 by Arbour & Briggs (2007) and classified as a type-II supernova a few days after explosion by Harutyunyan et al. (2007a). The spectrum (see Figure 4.27, bottom panel) consists of a blue continuum overimposed by P-Cyg profiles of H-Balmer and He I 5875Å lines. The expansion velocities deduced from H_α and H_β minima are about 11700 and 10800 km s^{-1}, respectively. The best match of this spectrum is that of the type-II SN 2005ay 9 days after explosion (Bufano et al. 2007).

SN 2007bg was discovered on Apr. 16.15 by Quimby et al. (2007). Edelmann & Terrazas (2007) re-

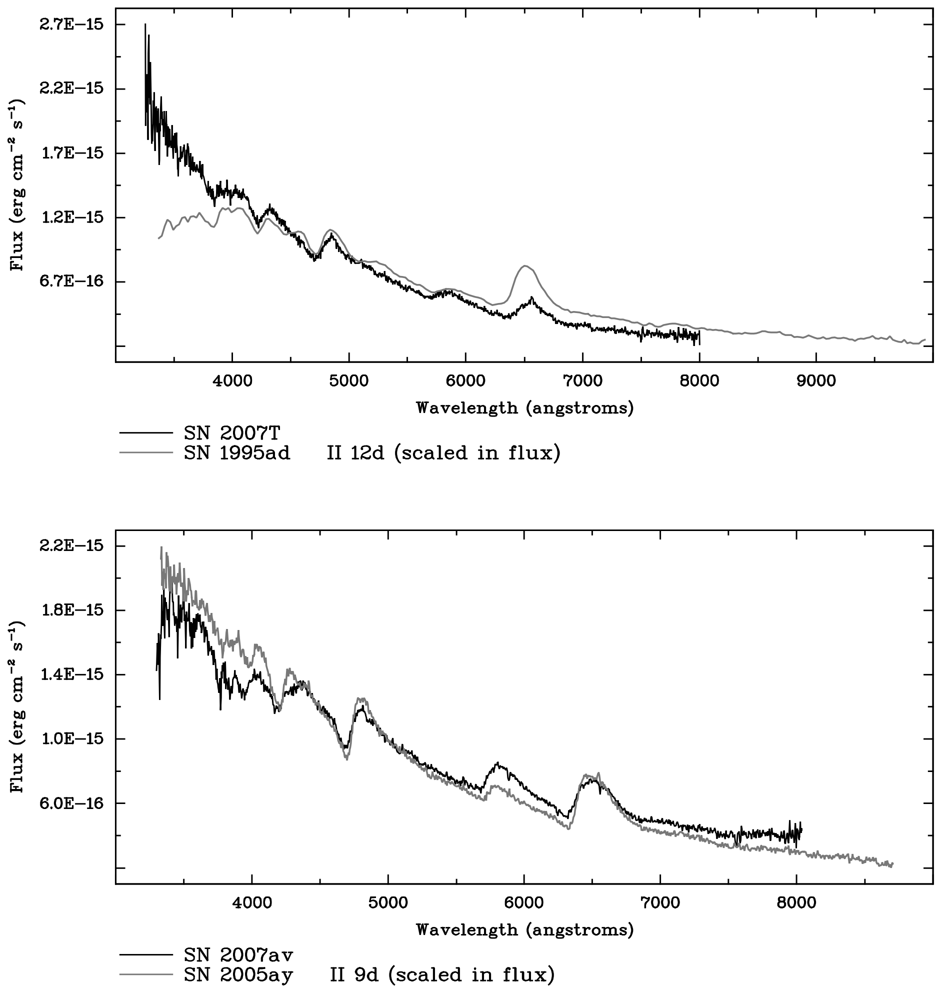


FIGURE 4.27– Same as Figure 4.19 for SN 2007T (top) and SN 2007av (bottom).

ported that the spectrum is similar to that of 2002ap 11 days after maximum and classified SN 2007bg as a type-Ic supernova. They pointed that the absorption around 6100Å in 2007bg is significantly stronger, and the O I 7774Å absorption is much weaker than in 2002ap. Nevertheless, the classification as a type-Ia event was ruled out because of the lack of any discernible S II features. Our spectrum (see Figure 4.28, top panel) was taken few days later. The best fit (GoF = 1.2) to it is with the type-Ic SN 1998bw 19 days after maximum, which confirms its resemblance to energetic type-Ic supernovae / hypernovae. The spectrum is dominated by a broad and strong feature centered at about 6524Å. If it is identified with H_α (possibly blended with Si II), SN 2007bg might also be classified as an energetic type-II supernova, similar to SN 2003bg (Hamuy et al. 2003a). In this hypothesis, the position of the minimum of H_α would indicate an expansion velocity of about 18000 km s^{-1}. Also, the He I lines, at a slightly lower velocity (14000 km s^{-1}), are possibly detected.

SN 2007bw was found on Apr. 18.5 and classified by Antilogus et al. (2007) as a type-IIn supernova. Our spectrum obtained on 20/05/07 (see Figure 4.28, bottom panel) shows features due to H_α, H_β, Ca

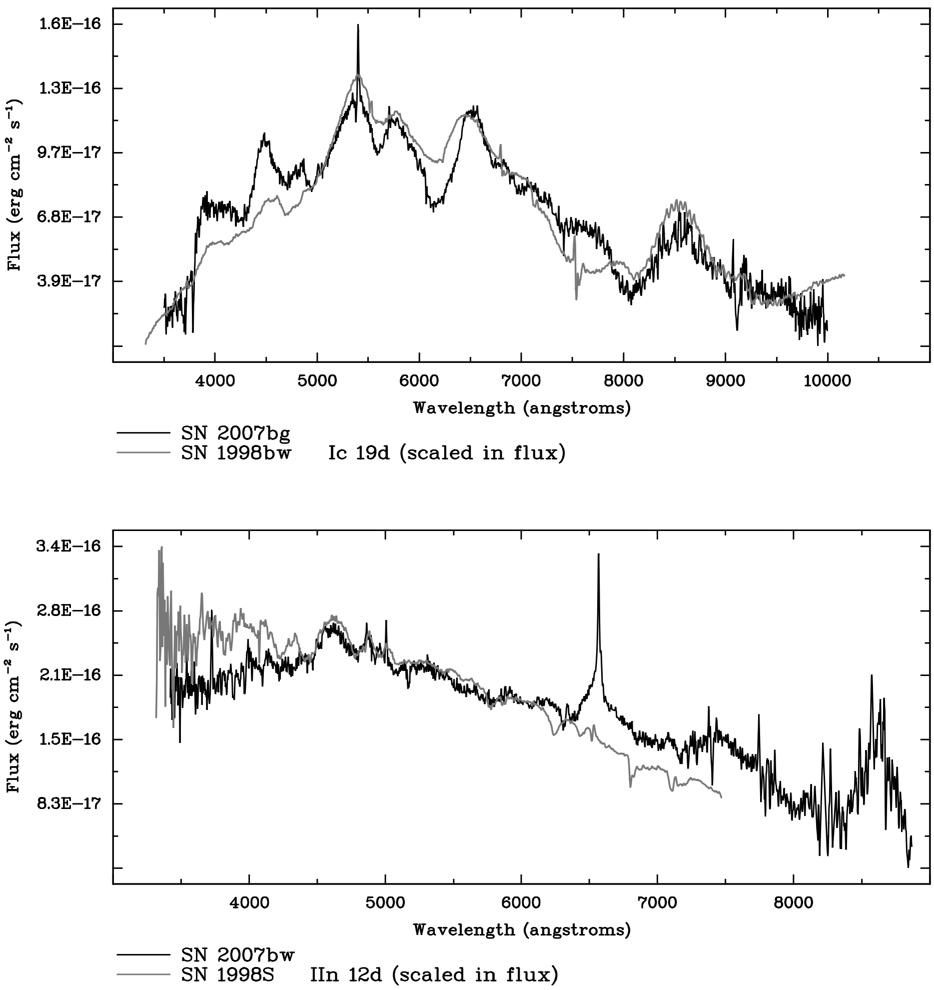


FIGURE 4.28– Same as Figure 4.19 for SN 2007bg (top) and SN 2007bw (bottom).

II, Ba II, Na I and Fe II. H_α has a complex profile consisting of three emission components: a narrow unresolved one, an intermediate (FWHM about 2800 km s^{-1}) one, and a broad one (FWHM about 1000 km s^{-1}). The best fitting template is the type-IIn SN 1998S spectrum 12 days after maximum (ASA), which fits well SN 2007bw in 4000-6000Å range, but lacks the entire H_α emission.

SN 2007cs was discovered on Jun. 24.49 by Winslow & Li (2007) and classified as a type-Ia supernova with very high expansion velocity by Harutyunyan et al. (2007e). The features due to Si II, Fe II, O I and Ca II are present in the spectrum (see Figure 4.29, top panel). The best match found by GELATO is type-Ia SN 1997bp 19 days after maximum (ASA; for the epoch of maximum see Altavilla et al. 2004). Despite the rather low fit quality (GoF = 1.1), the template shows the same spectral lines at similar expansion velocities, the only exception is the Fe II feature at about 5000Å, missing in the SN 2007cs spectrum. Also, the phase estimate (19 days) seems to be plausible because of the strong Fe II features. The expansion velocity derived from Si II 6355Å absorption minimum in the SN 2007cs spectrum is about 15000 km s^{-1}, very high for such a phase. In fact, SN 1997bp (the best fitting template)

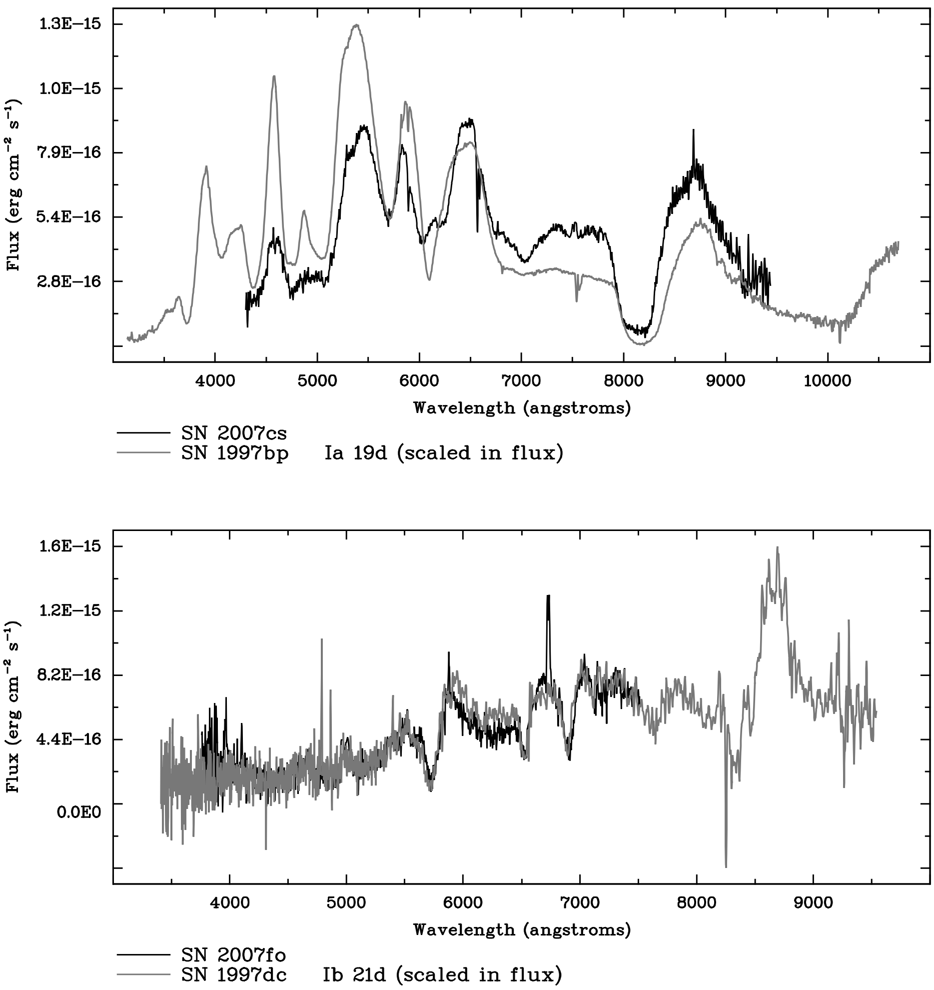


FIGURE 4.29– Same as Figure 4.19 for SN 2007cs (top) and SN 2007fo (bottom).

belongs to the HVG group (see Benetti et al. 2005). A strong Na I D interstellar absorption doublet (EW $\approx$ 2.7Å) found at the host-galaxy restframe suggests that the light of SN 2007cs is extinguished.

SN 2007fo was found on Jul. 9.43 by Khandrika & Li (2007). Desroches (2007) classified it as a type-Ib supernova admitting that a Ic event is also possible, though in the spectrum prominent He I features are present. Our spectrum (see Figure 4.29, bottom panel) taken 1 day later confirms the presence of He I lines at 5015Å, 5876Å, 6678Å and 7065Å with an average expansion velocity of about 7500 km s^{-1}. The strong He I features and the relatively low expansion velocity are consistent with the type Ib classification at around maximum light. The best match to this spectrum is that of the type-Ib SN 1997dc (Matheson et al. 2001), for which, however, a phase of 21-33 days after maximum is estimated.

4.2.3 Summary

In this section I presented the results of our SN classification program at TNG, which was aimed to fast characterisations of newly discovered objects. Such a fast characterisation was needed to select targets for more extended observational programs. I used GELATO during this program to classify the spectra, determine the phase of the SN, reddening and eventual peculiarities. GELATO's fast, "real-time" classification was very satisfying. Within few minutes GELATO gave information on the type and age of every object, providing the list of the best fitting templates and, thus, also allowing to determine whether the object was peculiar and / or worth to be followed..

A total of 13 objects were observed and classified during the program, 11 electronic circulars with classification results and other essential data like reddening and expansion velocity were sent to the CBAT. As expected, most of the observed SN were rather ordinary events for which no follow-up observations were later done. However, our classification program highlighted some outstanding explosions.

Two extraordinary events, SN 2006gy and SN 2006jc were classified during this program. The fast classification and characterisation of these two objects played a fundamental role in triggering and coordinating the follow-up observations. Their early (earliest) spectra obtained during our program were themselves very valuable for the study. Based on the data collected during the observational monitoring of SN 2006gy and SN 2006jc important results have been (or being) obtained, that require unprecedented SN progenitor scenarios and explosion mechanisms. The immediate consequences of these studies are the ineluctable updates of the current SN classification scheme with new SN classes.

As mentioned in Section 2.1, the Padova SN group has started a large observational program at TNG from the August 2007. A total of $\sim$14 nights of observational time will be granted to the program (long-term program) for each semester for a total of two years of granted time. Taking into account the success of our classification program at TNG, we decided to ask for ToO time as well. As a result, a classification program to be performed in ToO mode is an integral part of the long-term project.

4.3 Supernova 2002ic: the collapse of a stripped-envelope, massive star in a dense medium?*

In this chapter I present the work devoted to the accurate analysis and new classification of SN 2002ic. The nature of this peculiar SN has been a subject of long debates in literature. During the study, the objective classification of SN 2002ic spectra performed by our comparison software became an important tool supporting the re-classification of the SN.

The observations of SN2002ic, an alleged type-Ia SN showing the unambiguous signature of hydrogen lines in the spectrum, were claimed to mark a point in favour of the SD scenario (Hamuy et al. 2003b). The unusual spectrum of this SN has been explained by the composition of the spectrum of a typical SN Ia plus a contribution due to the interaction of the outer ejecta with a dense H-rich CSM. The occurrence of the ejecta-CSM interaction is also seen in the complex profile of the Hα emission: a narrow component on top of a very broad base (Hamuy et al. 2003b). With time, the contribution due to interaction becomes dominant, the underlying SN Ia spectrum was washed out, and eventually, two months after the discovery, the spectrum of SN 2002ic closely resembles those of the strongly interacting SNe IIn 1997cy (Germany et al. 2000; Turatto et al. 2000) and 1999E (Rigon et al. 2003).

The detection of strong hydrogen lines in the spectrum of a thermonuclear SN has stimulated the speculations on the possible nature of the progenitor system. Among the proposed scenarios are the explosion of a WD in a binary system with a post-AGB companion (Hamuy et al. 2003b), the explosion

*the material of this section is published in Benetti et al. (2006b)

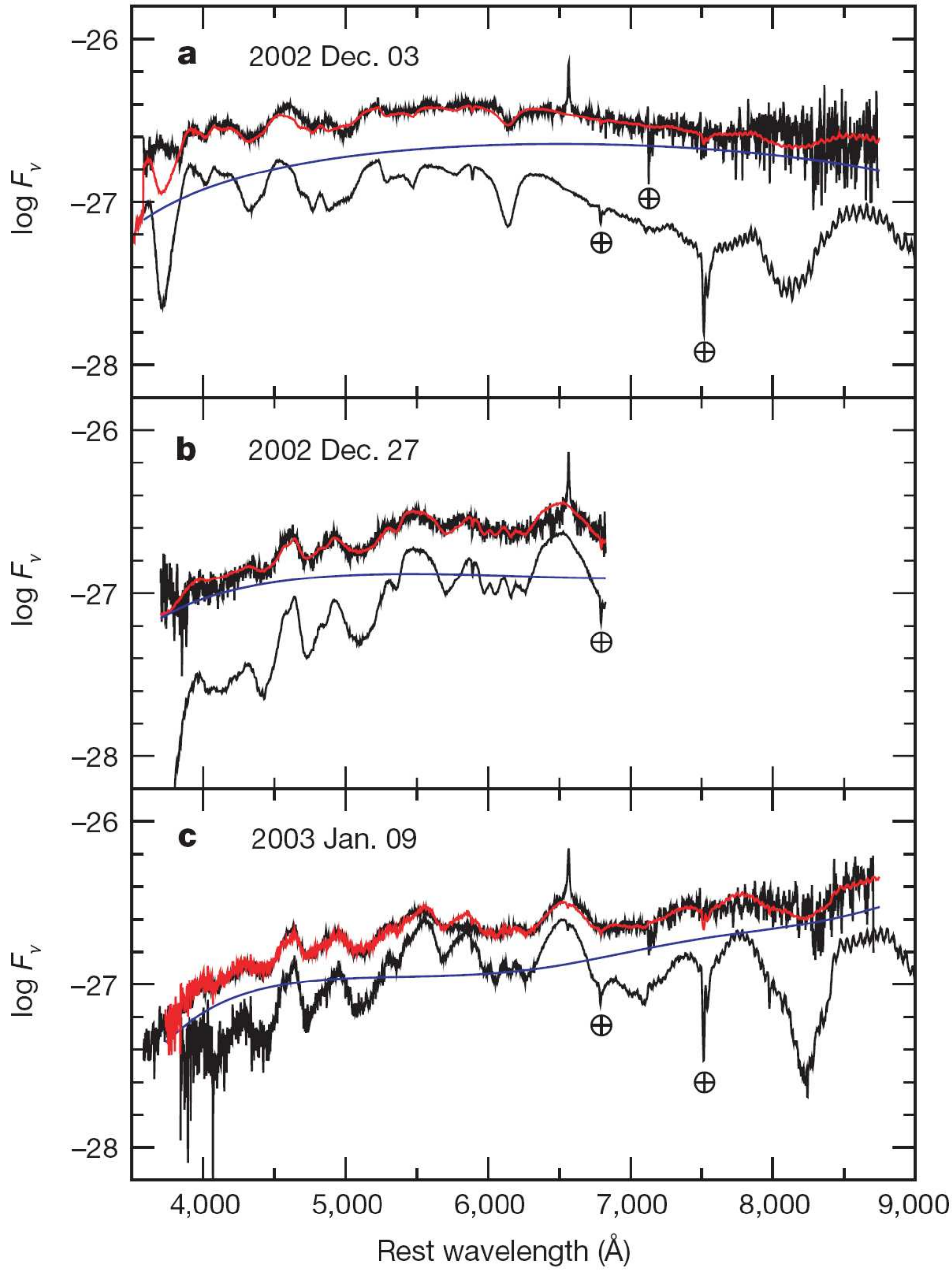


FIGURE 4.30– (a) Spectrum of SN 2002ic taken on 2002 December 3 (heavy black line), that of the normal type-Ia SN 1999ee taken 6 days past maximum (thin black line) together with low order continuum and sum of the continuum with the type-Ia SN spectrum (the thin line overplotted on the heavy black line). (b) the same as above but comparing the spectrum of SN 2002ic obtained on 2002 December 27 with that of SN 1999ee taken 34 days past maximum. (c) Same as above, except comparing the spectrum of SN 2002ic taken on 2003 January 9 with that of SN 1990N obtained 47 days past maximum (from Hamuy et al. 2003b).

of a C/O core of a $25M_\odot$ star (SN1.5, Hamuy et al. 2003b; Imshennik & Dunina-Barkovskaya 2005), the merger of a WD with the core of an AGB star (Livio & Riess 2003) and the explosion of a WD in a supersoft X-ray system (Han & Podsiadlowski 2006). In general, it is agreed that the discovery of hydrogen lines favours the SD scenario although the rareness of events like SN2002ic casts some doubts that they are really representative of all SNeIa (Livio & Riess 2003). So far only one more SN, SN2005gj (Prieto et al. 2005), has been found to show many similarities with SN2002ic (Aldering et al. 2006). In that case however, the features which were claimed to identify SN 2002ic as a type Ia were less evident and the first featureless SN 2005gj spectrum is reminiscent of those arising from the hot photospheres of CC explosions.

4.3.1 Was SN 2002ic really a type Ia SN?

Despite the deep implications of the observations of SN 2002ic, very little debate has taken place on the robustness of the proposed interpretation. It is true that the main features in the SN2002ic spectrum are fairly well reproduced by the composition of SN 1999ee spectrum, with its characteristic Si II and S II lines, and a (somehow arbitrary) continuum, but, at a closer look, there appear also some annoying discrepancies. In particular, the spectrum of SN 2002ic obtained in proximity to the maximum light does not show the strong H & K Ca II feature at $\sim$3700Å typical of SNe Ia (Figure 4.30a; from Hamuy et al. 2003b). About one month later (Figure 4.30b; from Hamuy et al. 2003b) a major discrepancy is seen around 6500Å: the broad emission attributed to Si II and Fe II in SNe Ia is much stronger than in the spectrum of SN 2002ic, where, for a direct comparison, one should also subtract the Hα contribution.

Starting from these inconsistencies, we have explored if other interpretations are viable.

The main argument for the classification of SN 2002ic as type Ia is the presence of the putative Si feature at 6150Å. Yet other SN types, in particular SNe Ic, usually associated to the collapse of bare CO cores, show a similar feature although the ion identification may be different (H_α, Branch et al. 2006). A recent, intriguing example was that of SN 2004aw (Taubenberger et al. 2006) which indeed on the basis of a single spectrum was initially (mis-)classified as slow decliner SN Ia, similar to SN 1991T (Benetti et al. 2004a). The error was corrected after considering the spectral evolution (Filippenko et al. 2004), and eventually the nebular spectrum, dominated by O and Ca emissions, definitely solved the ambiguity. However, it remains that the spectra of some SNe Ic at early phases can easily be confused with those of slow decliner SNe Ia.

Contrary to SNe Ia, SNe Ic show a wide range in their peak luminosities and intrinsic colors, and the reddening is hard to estimate. In the case of SN 2004aw, Taubenberger et al. (2006) adopted a color excess E(B-V)=0.37 based on a conservative relation between reddening and the equivalent width (EW) of the interstellar Na I D lines. The adoption of a steeper relation (Turatto et al. 2003) allows for a value as high as E(B-V)$\simeq$ 0.85, which has also the benefit of a better match of the color curves of SN 2004aw with those of other objects of the same type. Therefore, in the following, spectra and magnitudes of SN 2004aw have been corrected using this latter value. With this choice the absolute magnitude at maximum of SN 2004aw is even brighter than that of the hypernova SN 1998bw. We stress that the conclusion of our paper would not change significantly if we had adopted a different value for the reddening.

As an objective test we have applied the automatic classification software developed by our group (Harutyunyan et al. 2005) to the spectra of SN 2002ic. The spectra of SN 2002ic have been compared to those present in the whole Asiago-Padova Supernova archive, which contains about 2700 spectra of about 380 SNe of all types. The best match is found with the spectra of SN 2004aw, followed by those of SN 1997br, a slow declining SNIa similar to SN 1991T.

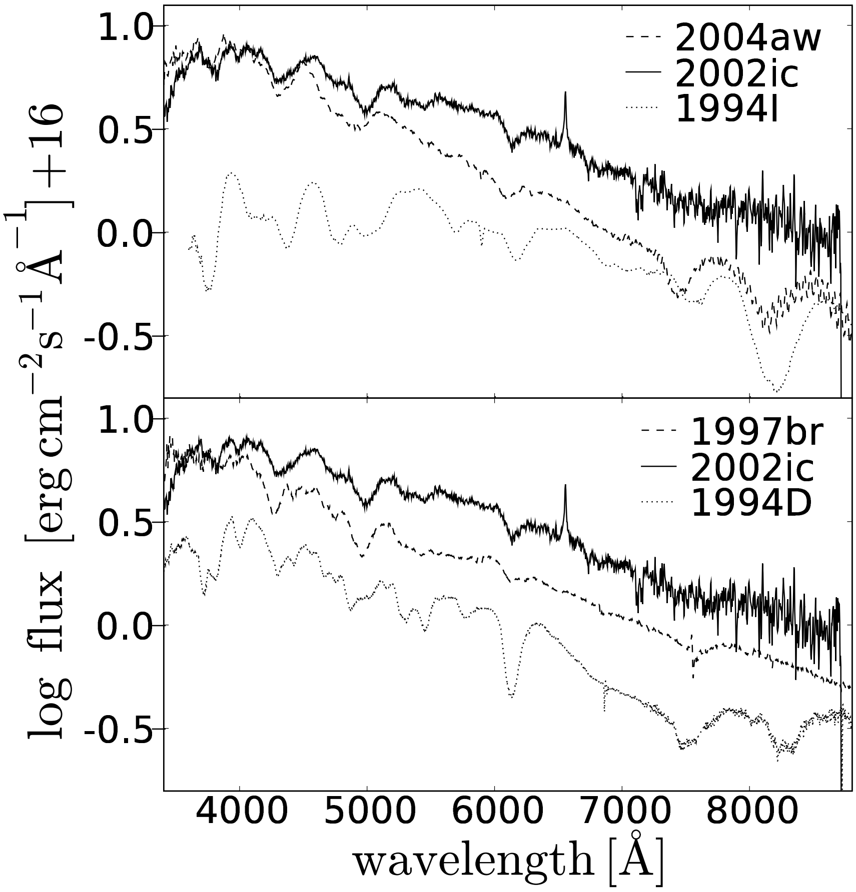


FIGURE 4.31– Comparison of maximum-light spectra of SN2002ic with those of the type Ic SNe 2004aw and 1994I (from ASA and McDonald archives) (top panel) and the type Ia SNe 1997br (from ASA) and 1994D (from Patat et al. 1996) (bottom panel). The spectra of SNe 2002ic, 2004aw and 1997br are in the parent galaxy rest frame, reddening-corrected and scaled in flux to the distance of SN2002ic assuming the following values: SN2002ic (2002/11/29): v_{hel} = 19800 km s^{-1}, E(B-V)=0.073, μ = 37.33; SN2004aw (2004/03/24): v_{hel}= 4900 km s^{-1}, E(B-V)=0.85, μ = 34.17; SN1997br (1997/04/16): v_{hel} = 2069 km s^{-1}, E(B-V)=0.35, μ = 32.25. The spectra of SN1994I and SN 1994D, corrected as above, are displayed as prototypes of the two classes (SN1994D (1994/03/19): v_{hel} = 450 km s^{-1}, E(B-V)=0.00; SN1994I (1994/04/09): v_{hel} = 461 km s^{-1}, E(B-V)=0.30).

Figure 4.31 shows the comparison at maximum light. In the top panel SN 2002ic is compared with SNe Ic, SN 2004aw and SN 1994I. The match with SN 2002aw is good concerning both overall appearance and flux intensity. The Si II line (or Hα) is in place as well as the two absorptions in correspondence to the S II lines although they are much shallower in SN 2004aw than in SN 2002ic. SN 1994I, instead, is definitely redder and shows more developed bands not entirely matching those of SN 2002ic. This is not surprising considering the broad range of properties of SNe Ic.

The comparison of SN 2002ic with SNe Ia is also very interesting (Figure 4.31 bottom panel). SN 1997br, whose spectrum is dominated by Fe II and Fe III lines, produces a generally good match: the SII lines at $\sim$ 5500 Å and the H & K Ca II absorption are weaker than in normal SN Ia. Instead, the match with the spectra of the typical SN 1994D is definitely not as good.

SN 2004aw spectrum is certainly a better match below ~ 4500Å, while SN 1997br better reproduces the featureless continuum above ~ 7000Å. The fact that both objects produce satisfactory fits to the spectrum of SN 2002ic is not surprising in the light of the misclassification of SN 2004aw mentioned above.

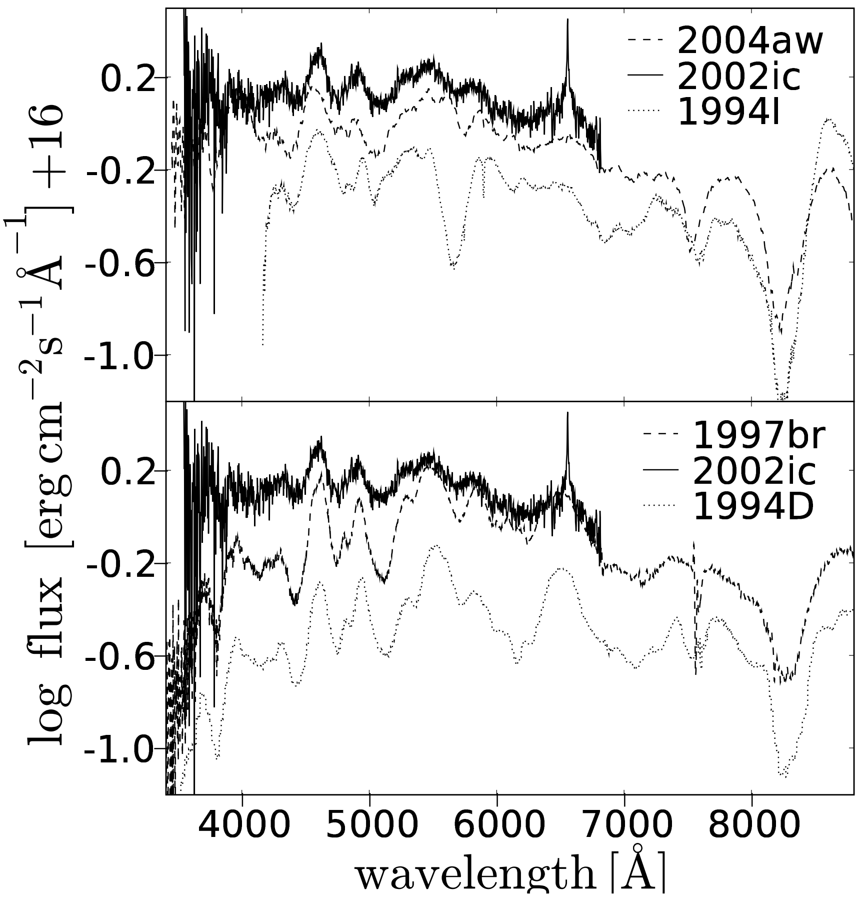


FIGURE 4.32– Comparison of the 1-month spectrum of SN 2002ic (2002/12/27) with those of the type Ic SNe 2004aw (2004/04/20) and 1994I (1994/05/03) (top panel), and the type Ia SNe 1997br (1997/05/13) and 1994D (1994/04/14) (bottom panel). See Figure 4.31 for additional information.

The comparison of the spectra taken one month later, shown in Figure 4.32, is more convincing. The SED of SN 2004aw well matches the spectrum of SN 2002ic with no need of any continuum. Some differences can be seen in the intensity of the Ca II line at ~ 4000Å and in the Na I D line at ~ 5700Å, both stronger in SN 2004aw than in SN 2002ic, but the coincidence of strength and position of all other features is good. We note, in particular, that the broad asymmetric emission at the base of the narrow Hα of SN 2002ic is present also in 2004aw and that a weak, narrow Hα emission seems to remain in some SN 2004aw spectra. At this phase the spectrum of SN 1994I shows a huge Na I D - He I 5876Å feature seen neither in SN 2004aw nor in SN 2002ic. SNe 1997br and 1994D are quite similar to each other, as usually do SN Ia when deeper layers are exposed (Figure 4.32 bottom panel) and, both make a reasonable fit to SN 2002ic. However, the centre wavelengths of the broad emission at $\sim$ 6500Å (Si II, Fe II) is bluer by $\sim$ 50Å in the SN Ia. Moreover, as already mentioned, the intensity of their 6500Å emission is much stronger compared to that of SN 2002ic. In general, to have a better match at this phase, the SN Ia spectra have to be "diluted" by a continuum possibly arising from the interaction between the ejecta and the CSM as suggested in Hamuy et al. (2003b).

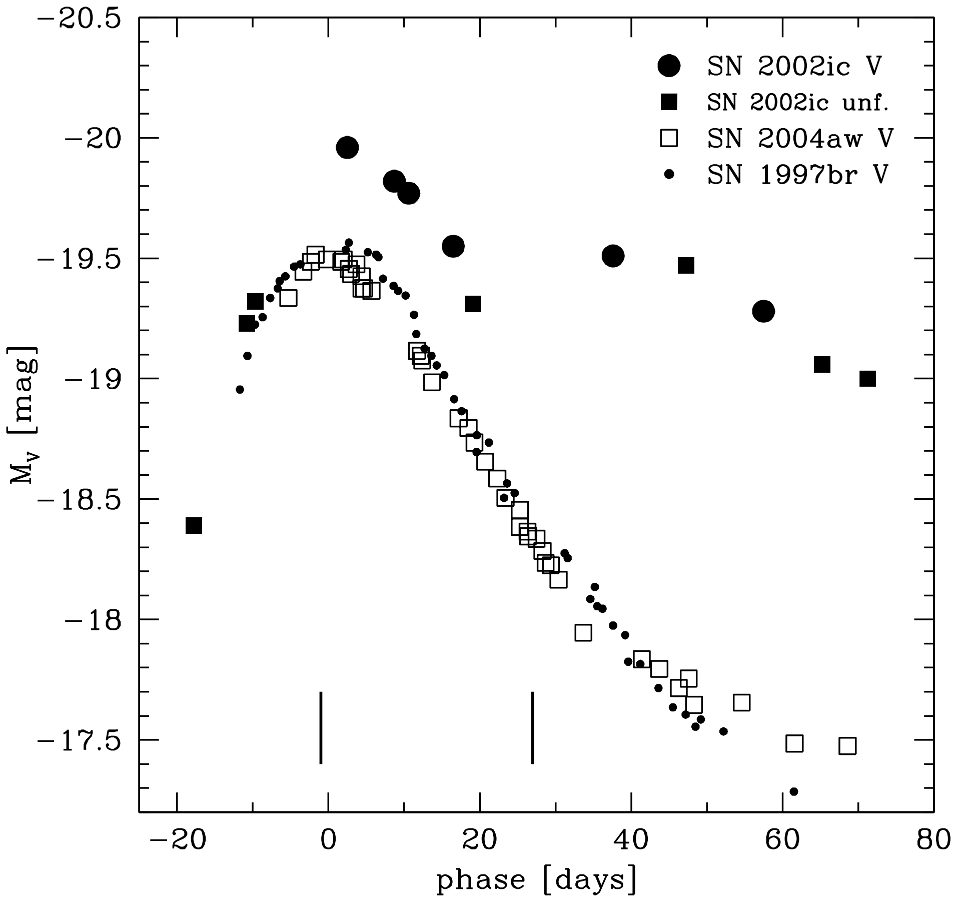


FIGURE 4.33– Comparison of the V absolute light curves of SNe 2002ic (Hamuy et al. 2003b; Wood-Vasey et al. 2004), 2004aw (Taubenberger et al. 2006) and 1997br (Li et al. 1999; Altavilla et al. 2004). The SN2002ic points have been K-corrected. Reddening and distance adopted for the three SNe are reported in the caption of Figure 4.31. The epochs of the two SN2002ic spectra shown in Figures 4.31 and 4.32 are marked with vertical lines.

We may note that the comparison of the light curves shown in Figure 4.33 is inconclusive for the identification of the nature of SN 2002ic. In fact the absolute V light curves of the type Ia SN 1997br and type Ic SN 2004aw are almost identical until almost two months from explosion. The light curve of SN 2002ic also has a similar shape, at least until 20 days after maximum, but appears 0.5 mag brighter.

4.3.2 The ejecta-CSM interaction in SN 2002ic

The re-brightening of SN 2002ic, occurring at about one month after maximum and attributed to the onset of a strong ejecta-CSM interaction (Hamuy et al. 2003b), averts the light curve from the normal decline of SNeIa and Ic (Figure 4.33). Indeed, the spectrum of SN 2002ic of Jan.9, 2003, is dominated by a strong Hα emission with broad wings and a blue continuum, and resembles that of a strongly interacting SN IIn.

Although at this point it becomes difficult to disentangle the intrinsic features of the SN from those of the CSM interaction, a comparative analysis of the late time spectra continues to support the idea that SN 2002ic was a CC SN of type Ic. In Figure 4.34 the spectrum of SN 2002ic obtained 10 months after the explosion is compared with spectra of the strongly interacting SN 1999E, the type Ic hypernova SN 1998bw, SN 2004aw and the type Ia SN 1991T. Also for this spectrum we have run the automatic classification software. Once the Hα emission is masked, the best match is with SN1998bw (SNe 1997cy and 1999E spectra excluded). While Ca lines are common to all SN types, we believe that the presence of Mg and O emissions, although not as strong as in normal CC SNe (probably because of the different physical conditions, higher density, due to interaction) are an indication that considerable amounts of intermediate mass elements are present in the shocked ejecta and CSM of SN2002ic, thus supporting the massive progenitor scenario. We have to remind that, on the other hand, Chugai et al. (2004) have modelled the late spectrum of SN2002ic with a mixture of iron group elements plus Ca, reproducing the quasi-continuum and the CaII features with the noticeable exception of the MgI] at 4600Å. Note that the oxygen expansion velocity deduced from the [O I] $\lambda\lambda6300, 6364$ emissions in SNe 2004aw and 1998bw ($\sim$ 7200 km s^{-1}) is comparable to that of SN2002ic (Deng et al. 2004). Spectropolarimetry of this latter SN has shown that the hydrogen line emitting region is asymmetric (Wang et al. 2004), which may be due to asymmetries either of the explosion or of the CSM, similarly to SN1999E, for which the asymmetric collapse of a CO core was proposed (Filippenko 2000).

4.3.3 Discussion

Although the SN Ia scenario proposed by Hamuy et al. (2003b) cannot be ruled out by our analysis, we do believe that there are evidences in favour of the association of SN 2002ic to a type Ic SN surrounded by a structured H-rich CSM, possibly asymmetric.

At early epochs SN 2002ic interacts only weakly with the fast wind of the progenitor star, as observed also for other SNe Ib/c in radio and X-rays (Filippenko 2000). After one month the interaction reinforces, likely because the ejecta reach a circumstellar shell of higher density. From that moment on, the light curve of SN 2002ic (Wood-Vasey et al. 2004) closely resembles that of SN 1997cy, for the which modelling requires a few solar masses of H-rich material (Turatto et al. 2000) in the CSM. The dense CSM is likely the relic of a powerful stellar wind which was active until shortly before the explosion. It has recently been realized that the He cores of massive, rapidly rotating stars can considerably increase in mass. In such cases violent explosions can take place at the ignition of oxygen burning, leading to the ejection of some solar masses of surface material (probably He-rich) months or years before the SN explosion (Woosley & Bloom 2006). Observational evidences that some massive stars undergo violent mass-loss episodes soon before explosion are also available (Benetti et al. 1999).

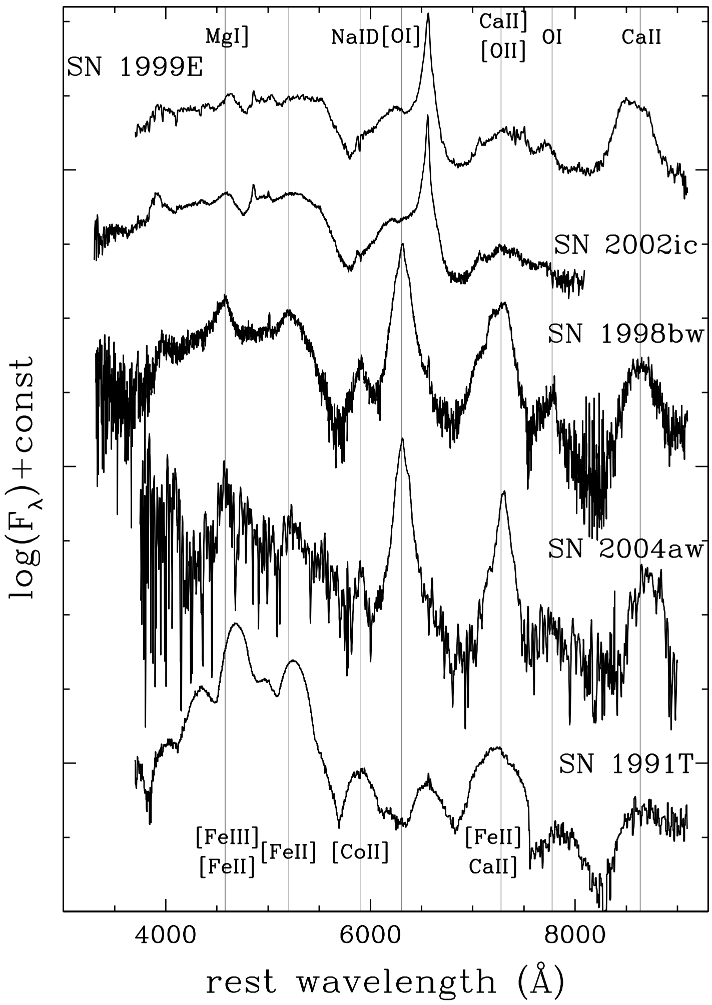


FIGURE 4.34– Comparison of late time nebular spectrum of SN 2002ic (ϕ = +241d; Wang et al. 2004) with those of SN 1999E (ϕ = +237d; Rigon et al. 2003) (IIn), SN 1998bw (ϕ = +200d; Patat et al. 2001) (Ic peculiar), SN 2004aw (ϕ = +236d; Taubenberger et al. 2006) (Ic) and SN 1991T (ϕ = +283d; Turatto et al. 1996) (slow decliner Ia). The spectra of the SNe 1999E, 1998bw and 1991T have been reported to the parent-galaxy rest frame and reddening corrected as follows: SN 1999E: v_{hel}=7800 km s^{-1}, E(B-V)=0.27; SN 1998bw: v_{hel}=2550 km s^{-1}, E(B-V)=0.06; SN 1991T: v_{hel}=1736 km s^{-1}, E(B-V)=0.14 (Phillips et al. 1999). For others see caption of Figure 4.34. The most significant features of SNe Ic are indicated by vertical lines and labelled on top of the figure. Bottom labels indicate the position of the most important nebular SNIa features.

Alternatively, if the progenitor was in a binary system, the dense CSM might originate from the companion. Indeed, in the solar neighbourhood a large fraction of Wolf–Rayet stars, which are among the best candidates for SNIc progenitors, are in binary systems with hot companions (Moffat et al. 1986). Therefore, contrary to the low-mass, evolved-progenitor scenario, in the case of a young, massive progenitor the presence of a dense CSM is certainly not unexpected.

Our interpretation of SN 2002ic with a CC SN would remove this event from the list of arguments concerning the true nature of SNIa progenitors, for which direct information would remain absent.

On the other side, the metamorphosis of SN 2002ic would establish a link between energetic SNe Ic

(SN 2004aw) and highly interacting type IIn (SNe 1997cy, 1999E), which, in turn, would allow a new look to the proposed association of the latter SNe with two BATSE GRBs (Germany et al. 2000; Turatto et al. 2000; Rigon et al. 2003). Indeed, although there is no information on a possible GRB associated to SN 2004aw, the association of some long GRBs with energetic SNIc is now firmly established (Woosley & Bloom 2006). In this view, the remarkable similarity of the Jan.9 spectrum of SN 2002ic with the first available spectrum of SN 1997cy suggests that the two spectra have been obtained at a similar phase and is fully consistent with the epoch of explosion for SN1997cy inferred from its proposed association with the GRB970514. In the same respect, also the spectral analogies found at late times with SN 1998bw (Figure 4.34). are interesting.

Little credit was given to the association of some SNe IIn with GRBs (Woosley & Bloom 2006), mainly based on the theoretical argument that a large H envelope was expected to quench the relativistic jet which is supposed to originate the GRB. The presence of a cavity around the exploding star, as seen from the observations of SN 2002ic, may leave room for the jet to extend before it shocks into the CSM. SN 2001ke, associated to GRB011121, well fits in this scenario. Indeed, Garnavich et al. (2003) found that the SED of this event about one month after the burst is similar to that of the highly interacting SN IIn 1998S. Moreover the overall appearance of the SN 2001ke spectrum is also reminiscent of those of SNe 2002ic and 2004aw taken at similar phases.

If these were common events, there should be a number of cases where the GRB optical afterglow would remain bright for a longer time than usually observed. Because this is not the case, we do not expect that strongly interacting type-IIn SNe are associated to a major fraction of long GRBs.

5

Summary

IN THIS THESIS I PRESENTED the tools for an automatic, objective classification of Supernovae developed by me for the Padova SN group, as well as several studies involving SN classifications, which made a wide use of these instruments.

To achieve the goal of objective classification, two crucial ingredients are required: a large number of SN spectra and a software performing spectra comparison. In our case, the first important component was provided by the large archive of SN spectra: the Asiago SN spectra Archive. I presented the archive, the current amount of the data, the SNe included in it and their main properties (types, redshifts, phases). The archive contains SNe of all types (including peculiar ones), spanning a wide range of properties and having a good temporal coverage. This is an important issue, since number and variety of SN spectra in the archive have a direct impact on the ability of the comparison software to identify a given SN. The large number of the spectra and their continuous additions to the archive required automatic procedures for the data management, and I overview the software developed by me, for organisation, update and enrichment of the archive data.

The other indispensable component for the objective classification is the software performing the comparison of spectra. I presented the collection of software procedures performing automatic SN spectra comparison, the PAdova Supernova Spectra comPARison TOOls (PASSPARTOO). These procedures, designed for different purposes and working with slightly different algorithms, carry out an automatic comparison of a given spectrum with all the spectra of our archive, mentioned above. Three procedures were described, as well as the differences in their design and the results obtained by them.

Moreover, I made a detailed presentation of the most frequently used procedure, GELATO, and its algorithm, optimised for classification of SNe. In particular, the creation of the templates, using an almost lossless technique of SN spectra processing was presented. Further, the methods of finding the best match template and of a quantitative evaluation of goodness-of-fits were described. Not only I showed the GELATO's ability for SN classification, but also its potential to estimate the ages of SN spectra. The chapter is concluded by an overview of the spectra comparison procedures created by few other groups working on SNe. The differences of GELATO from those procedures are discussed, which highlight its innovative approach to the comparison of SN spectra. Further, the future improvements to our software are presented. Currently GELATO is routinely used by the members of Padova SN group for classification and ageing of new discovered objects, as well as for comparative studies of SN spectra.

I have shown how the combination of the above mentioned two components has been applied to our study of SNe. In particular, I describe how our tools were used for an analysis of SN spectra obtained by the European Supernova Collaboration. These spectra, containing valuable physical information of the corresponding events, have not been studied in detail and published before. The observational data, obtained by 7 different telescope-instruments combinations, were collected and reduced. Further, we extracted important information from the spectra, like the expansion velocities, reddening and possible peculiarities of the corresponding SNe. Also, using GELATO we verified the original classification of the objects and estimated their ages. Confirming and in some cases refining the classification of the objects, we established that two very interesting SNe Ia have been discovered early enough to deserve further follow-up observations by the collaboration. GELATO showed to be a valuable tool for this kind of "a posteriori" analysis. The results of this study leaded by me, will be published in A&A.

Further I present our SN classification program at Telescopio Nazionale Galileo leaded by me. The program, running for two periods, was aimed to the early-time observations of SNe and to selecting targets for further observational campaigns. The decisive attribute of this program was the fast response to every discovery of new nearby SNe. The prompt ToO observation requests of newly discovered SNe were followed by the rapid and efficient reduction of the data and, then, the the obtained spectra were classified using GELATO. The latter showed to be a fast and reliable instrument in such "real-time" application.

The program gave more than ten SN classification, which were submitted to the IAU CBAT. However, the most important achievement of the program were the classifications of two extraordinary objects and their subsequent selection for large observational campaigns. SNe 2006gy and 2006jc were, in fact, classified by my program as peculiar events, showing unprecedented properties. The further observations and detailed studies of the data obtained showed that these SNe were very peculiar objects, which leaded astronomers to suggest new class of SN progenitors and novel explosion mechanisms. Not only our classification program was crucial for the identification of these objects, but also the early-time spectra of these SNe obtained during the program were very important inputs for their study. While the studies to explain the explosion mechanism for SN 2006gy are still in progress, this object is believed to be caused by pair-instability processes in extremely massive stars. SN 2006jc, instead appears to be a member of a new family of objects called SNe Ibn. These objects are likely to be produced by the explosion of Wolf–Rayet progenitors still embedded in the He-rich material.

Further in the Thesis I present our study devoted to SN 2002ic, an object whose nature has been largely debated. The observational properties of the object were interpreted by an explosion of a type-Ia SN with a dense H-rich CSM around it. In the work published by Benetti et al. (2006b) we suggest a new classification for this SN as type Ic, i.e. a collapse of a massive star that has lots its external H / He mantle. This classification, different from the wider-accepted one, is, however, more consistent with the object's properties and its evolution up to very late phases. Moreover, this scenario, contrary to the other one, does not require any unusual configuration of the SN progenitor system at the moment of explosion. During the study, the objective classification of SN 2002ic showing its similarity to the type-Ic SNe was one of the important clues, which suggested the true nature of this explosion.

5.1 Future work

We will enrich our SN archive with additions of new material coming from the various programs in which the Padova SN group is involved. The growing amount of the archive data will increase the power of statistical studies based on the archive itself. This growth will have a direct impact on the ability of our spectra comparison tools to identify SNe. I already mentioned that a large fraction of our archive spectra is contributing to the SUSPECT, an online, public database of SN spectra. However, we intend to make our own web interface to make our data public.

I have already discussed the future improvements to our spectra comparison software, which include the addition of more controls on the spectra pre-processing and refinement of the goodness-of-fit evaluation. New features like weighting of spectral bins and redshift evaluation will be also implemented. Finally, the software will be made accessible to the SN community. A web-based interface to the program is being developed, which will allow users to obtain fast type, phase (and redshift) determination of their own supernovae.

To have a progress in the study of physical properties of SNe a detailed spectrophotometric investigation of individual SNe is required. On the other hand, large archives contain an enormous amount of information buried under great deal of often unpublished observations. A complementary approach therefore, is the statistical one. It allows to determine groupings which cannot be seen in the case of single object approach. Only a comparative analyses of a set of spectra will provide the information about tendencies of SNe to cluster in new homogeneous sub-classes and in some cases will be helpful to find peculiarities.

We intend to exploit the potential of our large SN spectra archive and our tools of spectra comparison, to perform such kind of statistical study. All the spectra of the Asiago SN Spectra Archive will be compared to each other. Having for each SN spectra a quantitative value describing the degree of its similarity to the other spectra in the archive, we will use the techniques of cluster analysis, trying to organise the archive contents in groups. We expect that the comparisons of spectra will lead to the establishment of empirical groups, that may reflect the existing SN classes or will give evidences of new subclasses of objects, which have not yet been identified.

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