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The evolution of the cosmic SN rate

Enrico Cappellaro

INAF - Osservatorio Astronomico di Capodimonte, via Moiariello 16, 80131 Napoli, Italy
- e-mail: cappellaro@na.astro.it

Abstract. In this contribution, I briefly review the current status of SN taxonomy, report the latest estimates of the local SN rates and illustrate our ongoing project to measure the evolution of the SN rates with redshift.

Key words. Supernovae – Galaxy evolution – Star formation rate

1. Introduction

Supernovae (SNe) are at the crossroad of many different streams of astrophysical researches. In the last few years the emphasis has been on the use of SN Ia as cosmological distance indicators, but there are other hot topics in particular the new evidences for black hole formation in SN explosion or the link of (some) SN with (some) GRBs.

In this contribution I want to stress that because of the link of SN types with different stellar populations, the comparison of the SN rates in nearby and distant galaxies can give important information on the history of SN rate with cosmic age and hence on galaxy evolution.

2. SN types

Although the basic nomenclature of SN types remains that defined by Minkowski (1941), in the last two decades the increasing statistics and quality of observations has produced new branches and a number of *peculiar* events which are still waiting for a proper location. Recent reviews can be found in Hillebrandt & Leibundgut (2002) and Weiler (2003).

From a physical point of view the main distinction of SN types is between thermonuclear explosions (Ia) and core collapse events (II, Ib/c, ...) (see Fig. 1 for a synopsis of the main spectral features in templates of the different type).

The standard scenario for SN Ia call for a binary system where at least one of the component is an electron-degenerate dwarf (WD) which grows in mass either by mass transfer from the still evolving secondary star (single degenerate scenario; Whelan & Iben 1973; Nomoto et al. 1984) or by merging with a degenerate companion (double degenerate scenario; Iben & Tutukov 1984). If the WD manages to reach the Chandrasekhar limit, the ignition of the degenerate material (likely C-O) results in a thermonuclear explosion which destroys the star. This scenario has the advantage that, by tuning the system parameters, it is possible to delay the explosion for a time comparable to the Hubble time and hence explain the occurrence of SN Ia in systems where the star formation has ceased long time ago, like elliptical galaxies. The fact that the explosion occurs when the progenitor reaches a well defined configuration, can explain the uniformity of the observed events.

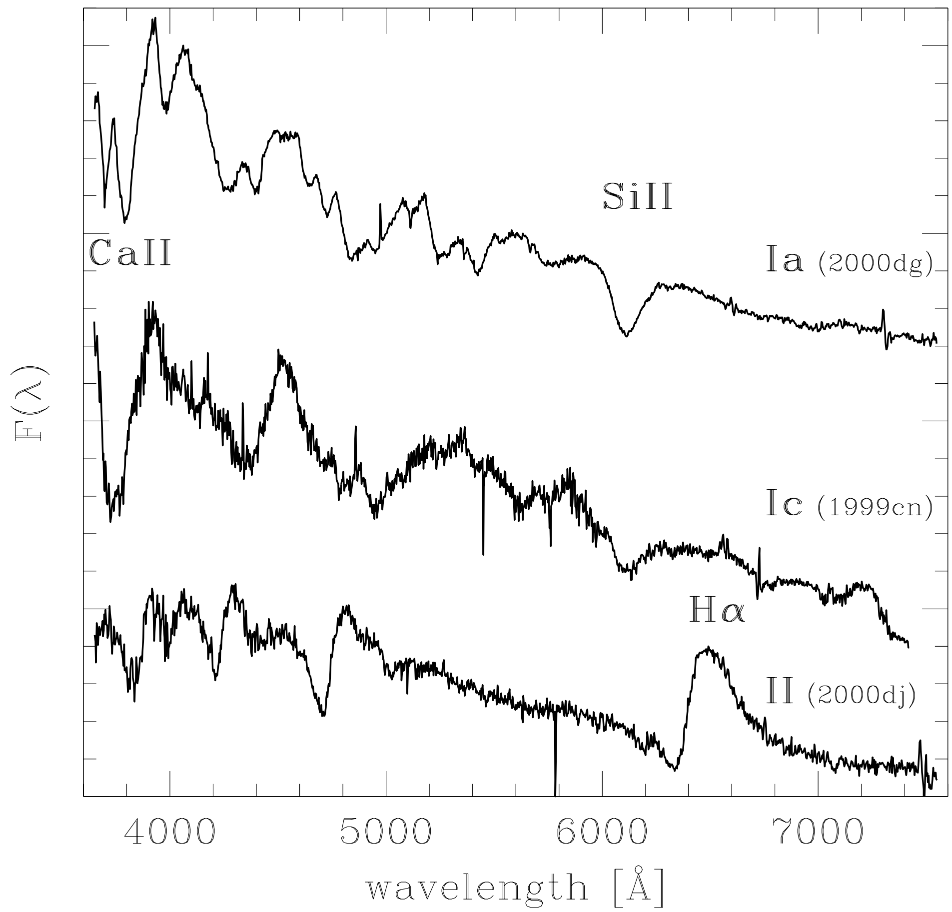

Fig. 1. Near maximum, type Ia show a deep absorption at 6150 Å attributed to the SiII 6355 Å doublet whereas type II show HI Balmer lines, in particular $H\alpha$. Those SNe where H or Si lines are not prominent are called Ib/c. In particular, type Ib are dominated by He lines, whereas the stronger features in type Ic are due to Ca. The spectra shown in the figure have been obtained at La Palma with the TNG+Dolores (SNe 2000dg and 2000dj) and with the WHT+ISIS (SN 1999cn).

In the last decade the use of SN Ia as cosmological distance indicators has brought the surprising result that the universe is accelerating (Perlmutter et al. 1999; Schmidt et al. 1998). An open problem is that the link of SN Ia progenitor with known binary systems has not yet been established (cf. Napiwotzki et al. 2001). This leaves some doubts that a possible evolution of SN Ia progenitors with cosmic age may result in dimmer events and hence mimics the effect of the Universe acceleration. To understand the physics of SNIa progenitor evolution and explosion through the detailed observation and accurate modeling of nearby SNIa is the purpose of a large European collaboration with the patronage of the European

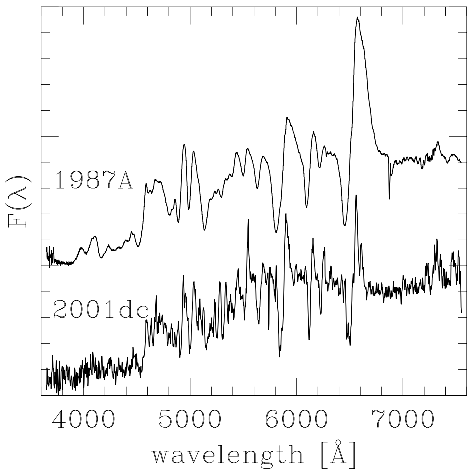

Fig. 2. The spectrum of SN 2001dc has been obtained at La Palma with the TNG+Dolores. The spectrum of 1987A from our ESO SN spectra archive is shown for comparison.

Research Training Network program (cf. http://www.mpa-garching.mpg.de/~rtn).

All SNe other than SN Ia are thought to originate from the collapse of massive stars ($> 8M_{\odot}$) that have exhausted the nuclear fuel (Heger et al. 2003).

The progenitors of most of the observed type II events are red super-giant stars in the range $10 - 25M_{\odot}$ which, after explosion, leave as collapsed remnant a neutron star. However, as shown by SN 1987A, the progenitor can also be a blue super-giant in the same mass range. Besides the radius of the star, the main ingredient determining the observed outcomes is mass loss. If at the time of explosion the star retains a large H envelope, this will store some of the explosion thermal energy that will be released when the envelope recombine. As a result the SN light curve shows a plateau (type IIP) of almost constant luminosity lasting up to 3-4 months. Instead, if only a small H envelope is left ($\sim 1M_{\odot}$) the light curve shows a linear decline in magnitude (type IIL). In all cases the late luminosity evolution is powered by the radioactive decay of ^{56}Co into ^{56}Fe.

Until some year ago it was believe that in most SN II the ^{56}Fe mass was of the order of $0.1M_{\odot}$. This belief has been challenged by the discovery of SN 1997D, a faint type II SN with a very small kinetic energy and Ni mass (Turatto et al. 1998; Benetti et al. 2001). The current understanding is that this event originates from a more massive progenitor that normal type II (Zampieri et al. 2003). It has been argued that because of the low explosion energy some of the ejecta falls back on the collapsed remnant. The latter grows above the mass limit for a stable neutron star and become a black hole. In principle, this hypothesis can be tested with observations because it is expected that the long term fall back onto the black hole gives a characteristic signature on the late light curve (Balberg et al. 2000). After SN 1997D a number of other similar events have been found (eg. SN 2001dc in Fig. 2).

In some cases, strong mass loss shortly before explosion may leave a very dense circumstellar material (CSM) which is quickly overrun by the fast expanding ejecta. In the shocked regions a fraction of the ejecta kinetic energy is converted into radiation slowing down the SN luminosity decline and changing completely the observed outcomes (type IIn). The spectrum (eg. SN 1999Z in Fig. 3) shows the superposition of narrow emissions originating in the shocked CSM, and broad emissions from the outer ejecta heated by the shock (Benetti et al. 1998; Aretxaga et al. 1999; Pastorello et al. 2002). By studying the evolution of type IIn it is possible to recover the history of mass loss in massive stars, a poorly known parameter of stellar evolution.

Recently two events have been discovered that, while similar to IIn in many respects, were exceptionally luminous, show evidences for very high expansion velocities and, most intriguing, had a (loose) association with GRB events (eg. SN 1999E in Fig. 3) (Turatto et al. 2000; Rigon et al. 2003). We should note however that current modeling seems to exclude that GRBs can emerge from a star with a massive H envelope (Woosley & Heger 2003).

Because of strong mass loss, very massive star ($> 40M_{\odot}$) loose all their H envelope and in extreme cases even the He envelope. These stars became the progenitors of Ib and Ic SNe respectively. Their near maxi-

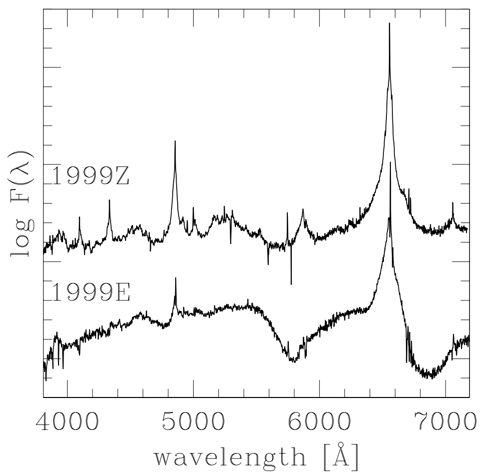

Fig. 3. Spectra of the type IIn SNe 1999Z and 1999E obtained at La Palma with the WHT+ISIS.

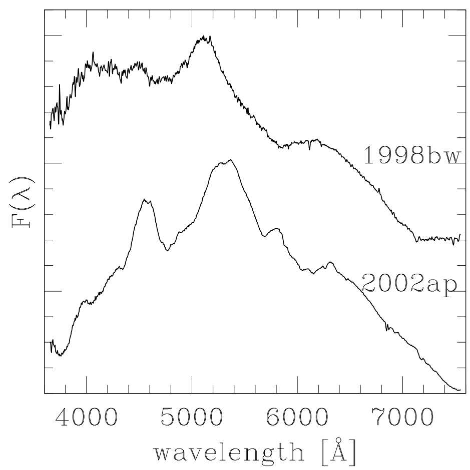

Fig. 4. Spectrum of SN 2002ap has been obtained at Asiago with the 182cm+AFOSC. The spectrum of 1998bw from our ESO SN spectra archive is shown for comparison.

mum spectra resemble that of type Ia SNe 2-3 weeks older, which is the historical reason of their designation. However, when they enter the nebular phase their spectra are dominated by lines of OI, CaII and MgII that is similar to that of SNII, but for the lack of H. The close relation between type II and Ib/c was demonstrated by transition objects like SN 1993J which show evidence of a very small H envelope (Filippenko, et al. 1993; Barbon et al. 1995).

The interest for stripped envelope SNe boosted after that in searching for the optical counterpart of GRB280498, SN 1998bw was discovered (Galama et al. 1998; Iwamoto et al. 1998). Early-on all spectral features were washed out by the extremely high expansion velocity, but then the SN evolved to a normal type Ic spectrum. Quite recently the afterglow of GRB030329 has been identified with SN 2003dh (Green 2003) which has a spectrum very similar to 1998bw. This strengths the association between core-collapse supernovae and at least some of the long-duration GRBs. Other SNe with spectra similar to 1998bw have been found for which no coincident GRBs event was registered (cf. SN 2002ap in Fig. 4).

3. Local SN rates

By modeling the evolution of individual stars and binary systems in a given stellar population, in principle, to predict the number of expected SN events. In turn, estimate of the rate of Supernovae can be use to constrain stellar evolution scenarios and/or the history of the star formation rate in galaxies.

To measure the rate of SNe requires a careful account for the biases affecting SN search programs. This is best achieved by considering only SNe discovered in a specific SN search for which all relevant information are available in particular the galaxy sample surveyed, the observing log, the limiting magnitude for SN discovery, etc. In addition, with the aim to study the relation between SN rates and the global properties of the parent stellar population, for each galaxy of the sample basic parameters such as distance, morphological type, luminosity, etc. must be available.

The draw-back of this approach is that the SN statistics get severely reduced. Thanks to the efforts of both intensive SN search program and large area galaxy surveys it will be possible, in the near future, to overcome this

Table 1. SN rates in the local Universe from Cappellaro et al. (1999) [SNu = SN $\times 10^{10} L_{\odot,B} \times$ 100yr].

galaxy	rate [SNu h^2_{75}]			
type	Ia	Ib/c	II	All
E-S0	0.18 ± 0.06	< 0.01	< 0.02	0.18 ± 0.06
S0a-Sb	0.18 ± 0.07	0.11 ± 0.06	0.42 ± 0.19	0.72 ± 0.21
Scd-Sd	0.21 ± 0.08	0.14 ± 0.07	0.86 ± 0.35	1.21 ± 0.37
All	0.20 ± 0.06	0.08 ± 0.04	0.40 ± 0.19	0.68 ± 0.20

limitation. To date, the winning strategy has been *i*) to extract the galaxy sample for an homogeneous catalog (de Vaucouleurs et al. 1991) and *ii*) count only the SNe discovered in a few, long term SNN searches (Cappellaro et al. 1997, 1999). Results are summarized in Table1. These numbers turned out to be fully consistent with the expectation from galaxy evolutionary scenarios. In particular, the high rate of core collapse SNe in late spirals reflects directly the change of the star formation rate with galaxy type (Kennicutt 1998).

Optical SN searches in dusty environments are severely biased. This brings a major uncertainty in the current estimate of the SN rate and may explain the discrepancy between observed and expected SN rate in dusty star forming regions such as the inner regions of starburst galaxies (Richmond et al. 1998). To address this issue, it would be useful to perform a SN searches in the infrared, where absorption is strongly reduced. This is not easy for two reasons: *i*) adequate infrared instrumentation is still of difficult access and *ii*) normal SNe at low redshift have little infrared emission. Likely, these are the reasons why only few attempts of infrared SN searches have been made so far, still with interlocutory results (Mannucci 2003).

4. High-z SN rates

In recent years, many authors have published predictions of the expected SN rate as a function of redshift based on SN progenitor scenarios and modeling of the cosmic star formation evolution (Madau et al. 1998; Sadat et al. 1998; Dahlén & Fransson 1999; Yungelson & Livio 2000; Kobayashi et al. 2000; Sullivan et al. 2000). It is disappointing that at the moment observational data to test these models are very scanty.

To date observational estimates of the SN rate at high redshift have been based on searches aimed to use SN Ia as cosmological probes (Pain et al. 1996, 2002). This has two drawbacks: *i*) they can provide estimates for the rate of type Ia only; *ii*) there are strong biases on the SN candidate selection. Indeed in most cases SN candidates are selected for spectroscopic confirmations only if they are not coincident with the host galaxy nucleus (to avoid contamination by variable AGN), the galaxy is not too bright (to make accurate photometry easier) and the candidate have blue color (to avoid uncertain reddening correction). Besides, only in one case the statistical error is small enough to make the measurement significant. This is the case of Pain et al. (2002) who, by using 38 SN Ia measured the rate at an average redshift z=0.55. They found $\nu(\mathrm{SNIa}) = 0.51^{+0.15}_{-0.13}$ SNu, that is a factor two higher than the local rate. Although this is a suggestive result we stress that, given the caveats mentioned above, it is not conclusive.

Because of this situation, some years ago we decided to start a SN search especially designed to estimate the rate of SNe of all types at intermediate redshift ($0.2 < z < 0.4$). A new opportunity came from the coming on

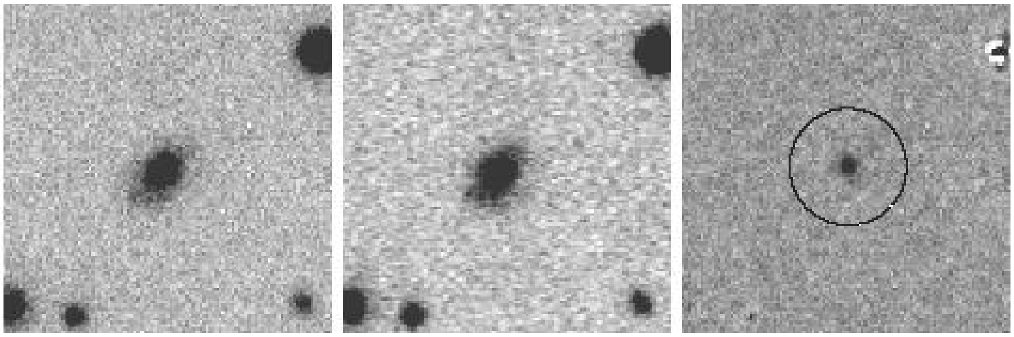

Fig. 5. The discovery of SN 2002cn. After subtracting from the image to be searched (left) the reference image (middle), the new object stands out (right). The box size is 25 arcsec.

line of the WFI at the ESO/MPI 2.2m telescope. Thanks to the wide field of view, 0.25 square degree, and the excellent spatial resolution, 0.24 arcsec/pix, the deep monitoring of a wide field area became feasible (in our case $\sim 2 - 2.5$ degree per run at $V \sim 24$).

The early part of the project was devoted to collect the reference exposures for each of 21 fields and in preparing the software for the data reduction.

We developed an automated pipeline including of the following steps:

1. the raw data were reduced using the *mscred* package in *IRAF* (Valdes 1998). For each field, the three dithered exposures were bias subtracted, flat fielded, astrometrically calibrated and combined.
2. the reference image is subtracted from the field to be searched. The most critical step is to match the PSF of the two images. This is done using the *ISIS2.1* package by Alard (2000).
3. residual point sources in the difference image are detected using the *sextractor* program (Bertin & Arnouts 1996)
4. the *sextractor* detection list is sorted using a custom made ranking program. The latter has been designed to remove false detections due to residual of saturated star or cosmic rays and has been tuned after extensive artificial star experiments.
5. the surviving candidates, typically a few tens per field, are visually inspected for final selection. Actually, most of the positive detections are variable stars. These are recognized based on the coincidence with a stellar source in the reference images. Eventually we are left with the SN candidates, typically from none to a handful per field.

An example of the output from our SN detection software is shown in Fig. 5.

Thanks to this preparatory work, in the second part of the project we were able to make the SN candidate detection almost in real time. This allowed to perform the spectroscopic confirmations for which we used VLT+FORS (eg. Fig. 6).

Actually, because of the limited VLT time available we could obtain spectroscopic observations only for $\sim 15\%$ of the about ~ 200 candidates detected. The effectiveness of the candidate selection criteria is demonstrated by the fact that out of the 29 candidates, 22 turned out to be SNe (about the same fraction of type Ia and core collapse and 7 variable AGN (Altavilla et al. 2003).

We notice that, because in our search we are trying to be as complete as possible, a significant contamination by AGN is unavoidable. To reduce this contamination we are maintaining a record of the variable sources of the fields. This allows to remove most variable AGN by considering their long term variability history.

After counting the SNe (and SN candidates) for each field and provided an accurate estimate of the SN detection efficiency (Riello

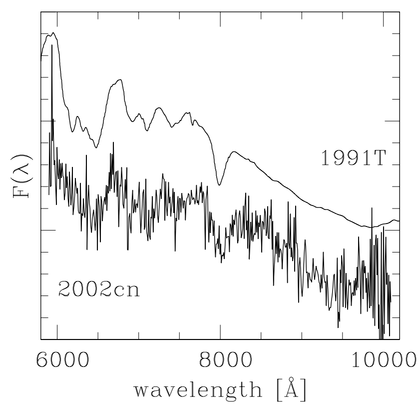

Fig. 6. Spectrum of SN 2002cn has been obtained with FORS2 at the Yepun VLT unit. The SN turned out to be a type Ia near maximum light at z=0.3032

et al. 2003), we are now working to derive a proper characterization of the galaxy sample, which is crucial for the comparison of high-z and local SN rates. The approach we are implementing makes use of the multicolor photometry to derive galaxy photometric redshifts.

With the work in progress we will be able to give the first estimate of the global SN rate at $z \sim 0.3$.

5. Future prospects

Measuring the rate of SNe as a function of redshift is a long term project. From one side one would like to collect a better statistics at redshift 0.3 <z< 0.6 where, given the current instrumentation, it is viable to obtain spectra of good S/N and hence a detailed SN classification. This will give the database to search for possible evolution of the SN progenitor population. An efficient search at these redshifts requires a wide field imager. In this respect the 1 square degree field of view of OmegaCAM at the VLT Survey Telescope (Kuijken et al. 2002) can give an invaluable contribution.

It is expected that a single, deep exposure with this instrument will recorde a dozen SNe. Clearly, obtain spectroscopic confirmation for all these candidates may not be feasible. Alternative approaches like a SN photometric classification may be required (Poznanski et al. 2002).

If one is able to test and calibrate this approach at intermediate redshift, it can became an invaluable tool for high redshift studies. This will be expecially interesting considering that by using the WFC at the LBT telescope (Ragazzoni et al. 2000) it will become possible to measure the SN rates up to z=1-1.5.

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References

Alard, C. 2000, A&AS, 144 363
Altavilla, G., et al. 2003 in From Twilight to Highlight: The Physics of Supernovae. Proceedings of the ESO/MPA/MPE, p. 400.
Aretxaga, I., et al. 1999, MNRAS 309, 343
Barbon, R., Benetti, S., Cappellaro, E., Patat, F., Turatto, M., Iijima, T. 1995, A&AS, 110, 513
Balberg, S., Zampieri, L., Shapiro, S. L. 2000, ApJ, 541, 860
Benetti, S., Cappellaro, E., Danziger, I. J., Turatto, M., Patat, F., Della Valle, M. 1998, MNRAS 294, 448
Benetti, S., et al. 2001, MNRAS 322, 361
Bertin, E., Arnouts, S. 1996, A&AS 117, 393
Cappellaro, E., et al. 1997, A&A 322, 431
Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A 351, 459
Dahlén, T., Fransson, C. 1999, A&A 350, 349
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Buta, R. J., Paturel, G., Fouque, P. 1991, Third Reference Catalogue of Bright GalaxiesSpringer-Verlag Berlin Heidelberg New York,
Filippenko, A. V., Matheson, T., Ho, L. C., 1993, ApJL 415, L103
Galama, T. J. et al. 1998, Nature 395, 670
Green, D. W. E 2003 IAUC 8114
Heger, A., Fryer, C.L., Woosley, S.E., Langer, N., Hartmann, D.H. 2003, ApJ in press, (astro-ph/0212469)
Hillebrandt, W., Leibundgut, B., (Eds.) 2002, From Twilight to Highlight: The Physics of Supernovae, Proceeding of the ESO/MPA/MPE Workshop

Iben, I., Tutukov, A. V. 1984, ApJS 54, 335
Iwamoto, K. et al. 1998, Nature 395, 672
Kennicutt, R. C. 1998, ARA&A, 36, 189
Kobayashi, C., Tsujimoto, T., & Nomoto, K. 2000, ApJ 539, 26
Kuijken, K., Bender, R., Cappellaro, E., et al. 2002, ESO Messenger, 110, 15
Madau, P., della Valle, M., Panagia, N. 1998, MNRAS 297, L17
Mannucci, F., Maiolino, R., Cresci, G., et al. 2003, A&A, 401, 519
Minkowski, R. 1941, PASP 53, 224
Napiwotzki, R. et al. 2001, Astronomische Nachrichten, 322, 411
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984 ApJ 286, 644
Pain, R., Hook, I. M., Deustua, S., et al. 1996, ApJ, 473, 356
Pain, R., Fabbro, S., Sullivan, M., et al. 2002, ApJ 577, 120
Pastorello, A., et al. 2002, MNRAS 333, 27
Perlmutter, S. et al. 1999, ApJ 517, 565
Poznanski, D., Gal-Yam, A., Maoz, D., Filippenko, A. V., Leonard, D. C., & Matheson T. 2002, PASP 114, 833
Ragazzoni, R., Giallongo, E., Pasian, F., et al. 2000, SPIE, 4008, 439
Richmond, M.W., Filippenko, A.V., Galisky, J. 1998, PASP 110, 553
Riello M., et al. 2003 in From Twilight to Highlight: The Physics of Supernovae. Proceedings of the ESO/MPA/MPE Workshop
Rigon, L., et al. 2003 MNRAS 340, 191
Sadat, R., Blanchard, A., Guiderdoni, B., & Silk J. 1998, A&A 331, L69
Schmidt, B. P. et al. 1998, ApJ 507, 46
Sullivan, M., Ellis, R., Nugent, P., Smail, I., Madau, P. 2000, MNRAS 319, 549
Turatto, M., et al. 1998 ApJ 498, 129
Turatto, M., et al. 2000 ApJL 534, L57
Valdes, F. G. 1998, in Astronomical Data Analysis Software and Systems VII, ASP Conf. Series, 145, eds. R. Albrecht, R.N. Hook and H.A. Bushouse (ASP: San Francisco), p. 7
Weiler, K., ed. 2003, Supernovae and Gamma ray bursters, Lecture Notes in Physics, vol. 598 Springer-Verlag - Heidelberg
Whelan, J., Iben, I.J., 1973, ApJ 186, 1007
Woosley, S.E., Heger, A. 2003, in Stellar Rotation, Proceedings IAU Symposium No. 215, eds. A. Maeder & P. Eenens (astro-ph/0301373)
Yungelson, L. R., Livio, M. 2000, ApJ 528, 108
Zampieri, L., et al. 2003, MNRAS, 338, 711