# Supernova and Gamma-Ray Burst Connections

# Optical and Near-IR Observations of SN 1998bw

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*Thus, the observation of gamma-ray line emission from a young supernova seems very promising in the near future. The observation, or even a null observation at a low threshold, will give significance in the fields of nuclear astrophysics and supernova theory. The scientific importance of a positive measurement would be analogous with and comparable to the importance of successful detection of neutrinos from the Sun.*

Clayton, Colgate, and Fishman [2].

**Summary.** SN 1998bw, especially after the discovery of GRB 030329/SN 2003dh, seems to be the equivalent of the Rosetta stone for the SN/GRB connection. In this paper I review optical and near IR observations that have been carried out for this uncanny object, which has probably confirmed suspicions and ideas originally formulated in the early seventies of last century.

## 1 Introduction

This story probably begins in 1969, with what I like to call a "prophecy," and it is right that I wish to start this review on the optical and near-IR observations of SN 1998bw[1].

As J. Sollerman said in one of his papers on this striking object, SN 1998bw was born famous. And it was doomed to become even more famous as time went by, so famous that it was sometimes named "the supernova of the century." And this is indeed interesting, since it was born in the same century of SN 1987A, one of the most studied and referenced objects in the sky.

Just from the optical and near-IR observations point of view, this is witnessed by the large number of papers which have been published in the first four years. Starting with the *Nature* papers by Galama et al. [7] and Iwamoto et al. [11], a number of authors have presented the results of their observational campaigns [5, 8, 16, 18, 21, 22, 23].

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[1] This talk was given in Valencia on 25 April 2003. For some cabalistic reason, this coincided exactly with the fifth anniversary of GRB 980425/SN1998bw.
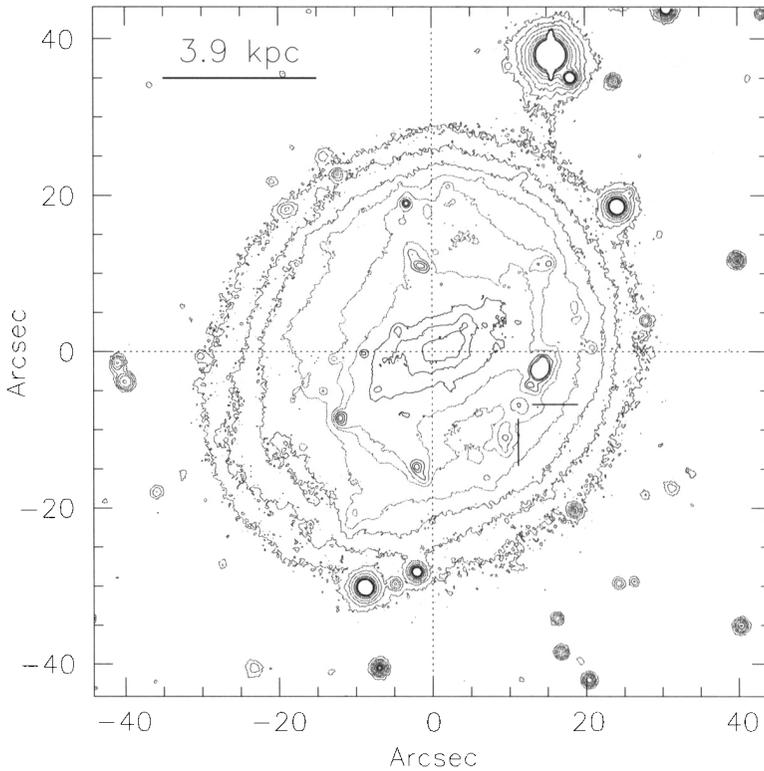
**Fig. 1.** Contour plot of ESO-184-G82. The original image stack was obtained at VLT+FORS1 at about 900 days after the explosion. Spatial scale was computed for a distance of 40 Mpc. The SN position is marked.

The reader is referred to these papers for a detailed account on the observations, while here I will try to give only a general view of the SN 1998bw phenomenon.

SN 1998bw was discovered by Galama et al. [6] in the BeppoSAX Wide Field Camera error box of GRB 980425 [19, 20] close to a spiral arm of the barred galaxy ESO 184-G82 (see Fig. 1), by comparing two frames taken at the ESO New Technology Telescope on Apr 28.4 and May 1.3 UT. Spectroscopic and photometric observations, both in the optical and in the near IR, started at ESO–La Silla immediately after the discovery, and showed that this object was profoundly different from all then known SNe [14].

Its peculiar spectroscopic appearance, its unusually high radio luminosity at early phases [13], its optical luminosity ($M_V \sim -19.2 + 5 \log h_{65}$) and, in particular, the probable association with GRB 980425 through positional and temporal coincidence [6, 19] placed SN 1998bw at the center of discussion concerning the nature of gamma-ray bursts (GRBs). The object was tentatively classified as a peculiar Ic [4, 17], I would say "by definition" more
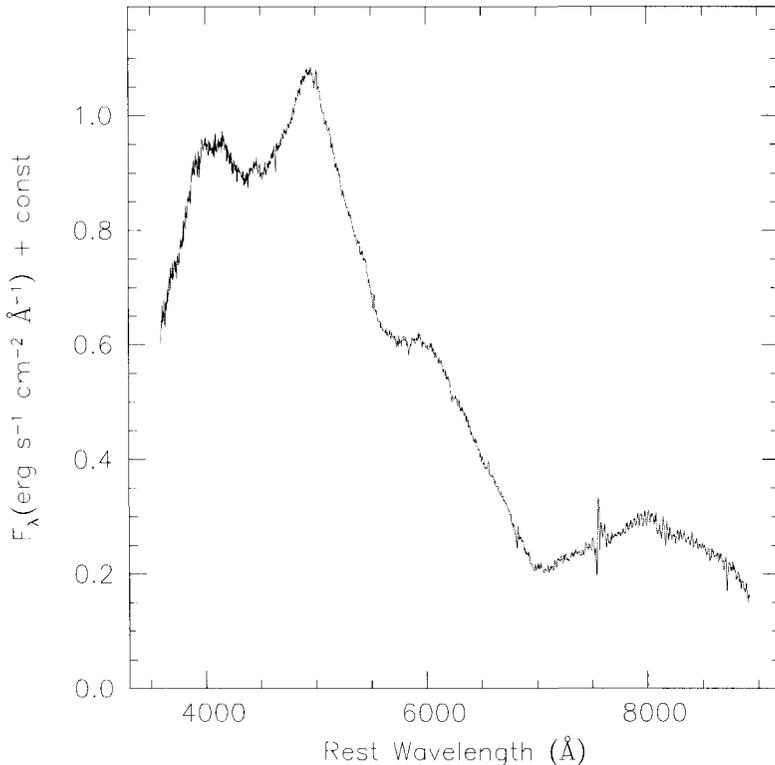
**Fig. 2.** Spectrum of SN 1998bw taken at ESO-La Silla on May 5, 1998.

than anything else, due to the complete absence of H lines, the weakness of the Si II 6355 Å line and no clear He I detection in the optical spectra (see Fig. 2). Main spectral features were identified as O I, Ca II, Si II and Fe II [11]. The estimated expansion velocities were exceptionally high ($\sim 30,000$ km s$^{-1}$) and this caused a severe line blending. The evolution during the first months was unusually slow compared to known Ic, with the nebular spectra still retaining many of the features present during the photospheric phase [18, 23].

The late onset of the fully nebular phase has been interpreted as an indication for a large ejected mass [23] as it was predicted by the early light curve models. During the intermediate phase, the emission lines were definitely broader than in known Type Ib/c SNe and the simultaneous presence of iron–peak and $\alpha$-elements indicated unusual relative abundances or physical conditions in the SN ejecta [18]. The late spectroscopy presented by [21] showed that the tentative morphological classification of SN 1998bw as a Type Ic event was indeed appropriate. The main features have been identified as [O I], Ca II, Mg I and Na I D, the latter possibly contaminated by He I 5876 Å.

As far as the gamma-ray burst is concerned, GRB 980425 was pretty weak, since the implied energy for a 40 Mpc distance was $8.1\pm1.0 \times10^{47}$ erg [19], which is definitely smaller than the usual $10^{53}$ erg value typical for the so-called cosmological GRBs. This has led the community to believe that GRB 980425 is a member of an unusual class of GRBs/SNe (see, e.g., [5]).

The galaxy which hosted GRB 980425/SN 1998bw, ESO 184–G82, is an SBc galaxy with a recession velocity $v_r = 2532$ km s$^{-1}$ [18]. Its luminosity is $L \sim0.5$–$1.2$ $L_{LMC}$, it is currently undergoing strong star formation, it shows a bar and rather clear indications of morphological disturbances [5]. This is clearly visible in the late VLT images, which show a possibly double nucleus, isophotal twisting and asymmetry (see Fig. 1). All this suggests that the observed star formation is related to galaxy interaction/merging.

The HST images have shown that SN 1998bw exploded in a star-forming region [5], containing several bright and young stars within a projected distance of 100 pc. This is consistent with the progenitor of SN 1998bw being a young and massive star

Due to its relatively high apparent brightness, Kay et al. [12] and Patat et al. [18] have attempted to perform some polarimetric measurements at different epochs. After correcting for the interstellar polarization in the direction of the host galaxy, the estimated optical linear polarization was 0.6% (day $-7$), 0.4% (day $+10$) and 0.5% (day $+42$). The fluctuations in these values seem to suggest that the observed polarization is intrinsic to the SN, although a dusty medium in the parent galaxy cannot be ruled out.

The small degree of polarization at optical wavelengths can be explained in terms of a moderate departure from sphericity (axial ratio less than 2:1 [10]), either in the photosphere or in the outer scattering envelope when the line of sight is not coincident with an axis of symmetry.

Interestingly, no polarization, either circular or linear, was detected in the radio, and this has been interpreted as the signature of a spherically symmetric blast wave [13]. This apparent discrepancy might suggest that the radio and the optical radiation were generated in regions of different geometry.

## 2 Photometric and Spectroscopic Evolution

The early light curve of SN 1998bw has shown that the object was unusually bright when compared to known SNe of type Ib/c [7] and, in this respect, it was much more similar to a type Ia. The broad-band photometric observations by [16] taken during the intermediate phases revealed that the object settled on an exponential decay similar to that observed in other type Ic SNe. McKenzie and Schaefer first suggested that even in this case the light curve was powered by the radioactive decay of $^{56}$Co with some leakage of $\gamma$-rays. Photometry covering later phases was then presented by [18, 21, 22],
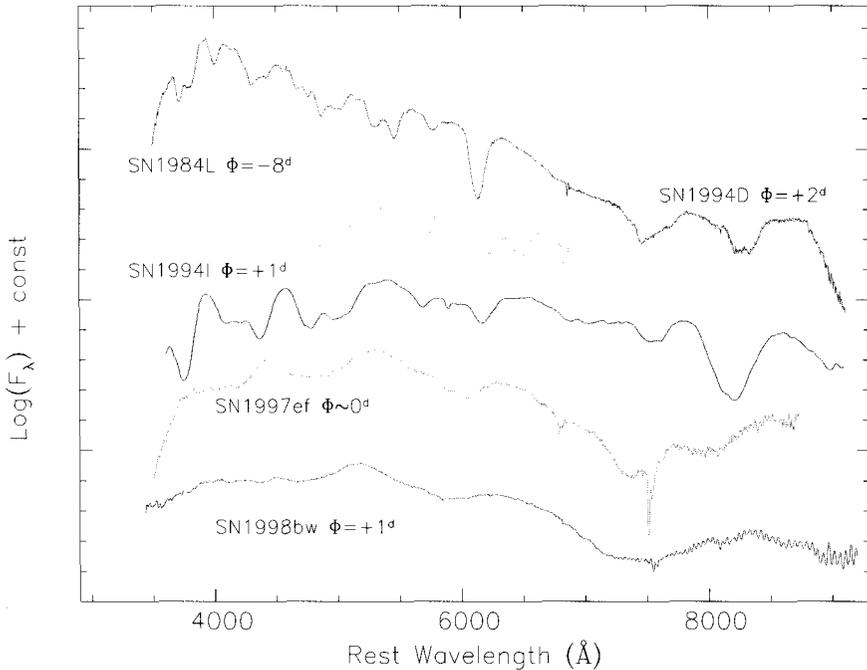
**Fig. 3.** Comparison between SN 1998bw and other SNe at maximum light.

the latter extending to ∼1000 days after the explosion by means of HST observations.

The late light curve continues to fall significantly steeper that the decay rate of $^{56}$Co up to more than 500 days. There is no sign of the so-called positron phase, in which the fully deposited kinetic energy from the positrons would dominate the light curve.

Another interesting feature is the light curve flattening observed at about 800 days past explosion. For a detailed discussion on the possible explanations, we refer the reader to the original paper by [22] and here we just mention them: onset of more long-lived isotopes radioactive decay (e.g., $^{57}$Co), freeze-out, interaction with CSM, black-hole powering and faint light echoes.

Using a simple radioactive model, Sollerman et al. [22] could fit the data with ∼0.3 M$_\odot$ of ejected $^{56}$Ni, which can be regarded as a lower limit to the amount of ejected nickel in SN 1998bw. In this respect we note that the early light curve modeling (see [11]) required ∼0.7 M$_\odot$ in order to reproduce the observed high peak luminosity.

Extensive spectroscopic data sets were presented by [18, 23]. The general appearance of the spectrum at maximum light is quite unique among SNe, even though it is somewhat reminiscent of SN 1997ef (see Fig. 3), which has been modeled as a massive SN Ic [15]. At these early epochs, when the velocity is high, line blending is particularly severe; the modeling presented
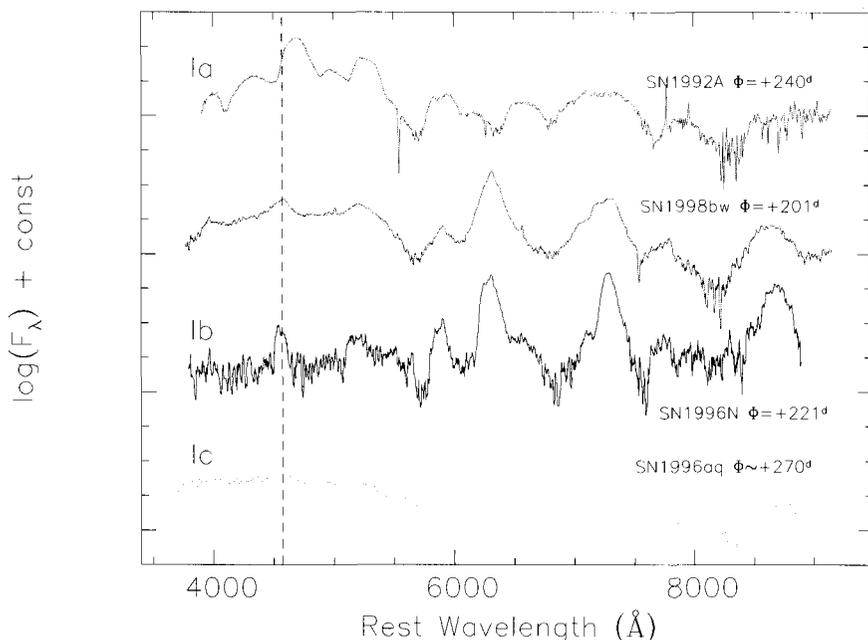
**Fig. 4.** Comparison between SNe 1992A (Ia), 1998bw, 1991N (Ib) and 1996aq (Ic) at late phases. The vertical dashed line is placed at the rest-frame wavelength of MgI]$\lambda$4571.

by [11] suggests that the main features are due to lines of Si II, O I, Ca II and Fe II. The velocity, deduced from the Si II $\lambda$6355 line is about 30,000 km s$^{-1}$ at day $-7$ and decreases to about 18,000 km s$^{-1}$ at day $+22$. These value are exceptionally high, for any SN.

   Starting at about one month after maximum light, the SN enters its nebular phase. The transition from an absorption to an emission spectrum is slow and subtle. While the evolution of SN 1998bw in the range $5500 - 9000$ Å is similar to that of SN Ic events, the expansion velocities are larger, and the region between 4000 and 5500 Å is dominated (at least until about day $+200$) by a wide bump to which Fe II transitions probably contribute significantly (see Fig. 4). In general, the spectral appearance supports the idea that this object is related to SNe Ib/c. It might be regarded as an extreme case among these objects, having large kinetic energy, ejecta mass and ejected mass of synthesized $^{56}$Ni, while SN 1997ef could represent a less extreme case closer in properties to the known SNe Ic.

   At one year, despite its early marked peculiarity, SN 1998bw is practically indistinguishable from known type Ib (see Fig. 5). Even the high expansion velocities measured during the first 6 months have slowed down to the values that are typical for other type Ib SNe ($\sim 5000$ km s$^{-1}$). But, the much higher ejected mass estimated by the models and the high luminosity, which persists
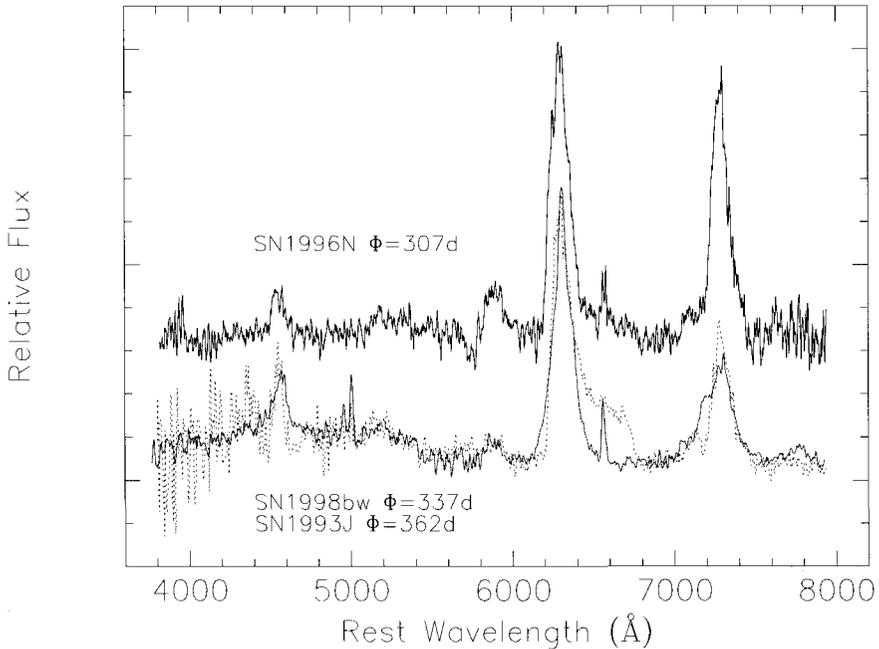
**Fig. 5.** Comparison between Type IIb SN 1993J (dotted line), Type Ib 1996N and SN 1998bw at about 1 year after maximum light. Spectra have been normalized to the [OI] $\lambda\lambda6300,6364$ peak and arbitrarily shifted for presentation.

also at these advanced phases (SN 1998bw is 3 mag brighter than SN 1996N at late phases), tend to support the idea of a hyper-energetic event.

An important aspect, which may give some hints about the progenitor's nature is the presence/absence of helium. The optical spectra have shown no traces of this element (see Fig. 6) and this is why the SN was classified as a Ic. On the other hand, near-IR spectroscopy $(1.0-2.5\ \mu\text{m})$ during the early phases has shown the presence of a strong emission accompanied by a P-Cyg profile, which might be He I 1.08 $\mu$m. This identification is somewhat supported by the detection of another He I line at 2.06 $\mu$m. However, alternative identifications are possible (see the discussion in [18]) and, therefore, the detection of helium in the spectra of SN 1998bw is not so firm.

## 3 A New Beginning

After finishing the work on SN 1998bw I had the impression that the show was over and we had met just another peculiar object with no future. And, more depressing, we were left with more questions than answers. But nature is subtle and a very recent GRB, named 030329, has shown clear traces of an underlying SN spectrum, indeed similar to that of SN 1998bw (see [9]
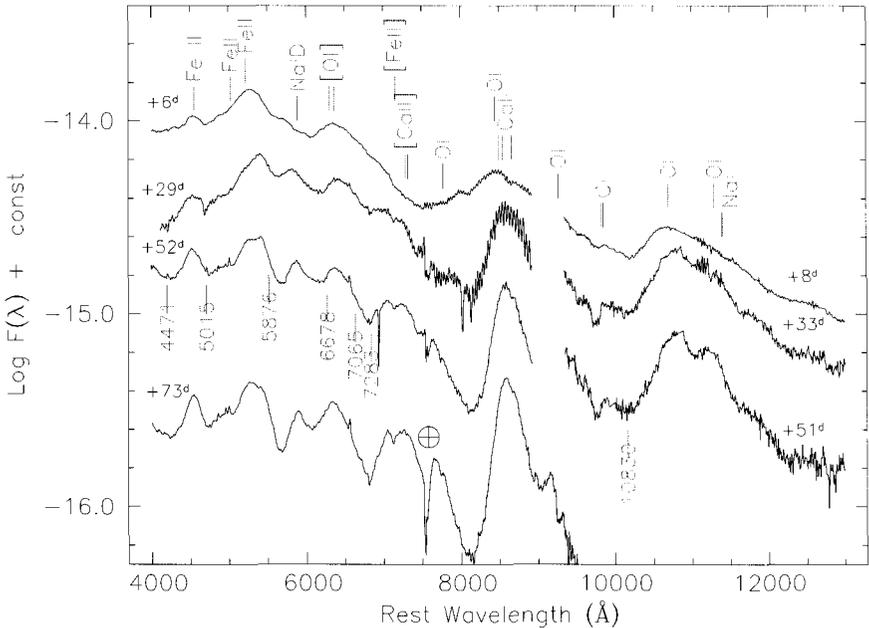
**Fig. 6.** Optical and IR spectra of SN 1998bw at comparable phases. Line identifications from spectral modeling are plotted for the most prominent emission features (top) and for the He I lines (bottom). The He marks are placed at the expected absorption positions for an expansion velocity of 18,300 km s$^{-1}$.

and the contribution by T. Matheson in these Proceedings). Even though GRB 030329 was among the brightest ever recorded (while GRB 980425 was extremely weak), the spectral resemblance to SN 1998bw is really astonishing.

This clearly indicates that, at least some GRB events are linked to core-collapse SNe and it confirms the ideas that were born with the discovery of GRB 980425/SN 1998bw and which have their original seed in the pioneering work by [1].

I have started this review quoting the paper by Clayton, Colgate and Fishman [2]. Actually, a few years later, in 1974, S. Colgate advanced the idea that $\gamma$-ray pulses of cosmic origin observed from the Vela spacecraft could be originated by the core-collapse of massive stars in distant galaxies [3].

Thirty years after, this prophecy seems to come true[2].

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[2] The first idea actually dates back to 1959, when S. Colgate gave a talk to the Russian delegation of the conference for the cessation of nuclear testing in space, suggesting that "SNe or something like them might trigger our treaty detectors in orbit, causing us to lob nuclear weapons at each other" (private communication).

**Fig. 7.** Stirling Colgate at Aiguablava (Spain) in 1995. Photo by the author.

# References

1. J.S. Bloom et al. : Nature **401**, 453 (1999)
2. D.D. Clayton, S.A. Colgate, G.J. Fishman: Astrophys. J. **155**, 75 (1969)
3. S.A. Colgate: Astrophys. J. **187**, 333 (1974)
4. A.V. Filippenko: IAUC 6969 (1998)
5. J.U. Fynbo et al.: Astrophys. J. Lett. **542**, L89 (2000)
6. T.J. Galama, P.M. Vreeswijk, E. Pian, F. Frontera, V. Doublier, J.F.Gonzalez: IAUC 6895 (1998)
7. T.J. Galama et al. : Nature **1395**, 670 (1998)
8. T.J. Galama et al. : Astron. Astrophys. Suppl. **138**, 465 (1999)
9. P. Garnavich, T. Matheson, E. W. Olszewski, P. Harding, K. Z. Stanek: IAUC 8108 (2003)
10. P. Höflich, J.C. Wheeler, L. Wang: Astrophys. J. **521**, 179 (1999)
11. K. Iwamoto et al. : Nature **395**, 672 (1998)
12. L.E. Kay, J.P. Halpern, K.M. Leighly, S. Heathcote, A.M. Magalhaes: IAUC 6969 (1998)
13. S.R. Kulkarni et al. : Nature **395**, 663 (1998)
14. C. Lidman, V. Doublier, J.F. Gonzalez, T. Augusteijn, O. Hainaut, H. Boehn-hardt, F. Patat, B. Leibundgut: IAUC 6895 (1998)
15. P.A. Mazzali, K. Iwamoto, K. Nomoto: Astrophys. J. **545**, 407 (2000)
16. E.H. McKenzie, B.E. Schaefer: Pub. Astron. Soc. Pacific **111**, 964 (1999)
17. F. Patat, A. Piemonte: IAUC 6918 (1998)
18. F. Patat et al. : Astrophys. J. **555**, 900 (2001)
19. E. Pian et al. : Astron. Astrophys. Suppl. **138**, 463 (1999)
20. P. Soffita et al. : IAUC 6884 91998)

21. J. Sollerman, C. Kozma, C., C. Fransson, B. Leibundgut, P. Lundqvist, F. Ryde, P. Woudt: Astrophys. J. Lett. **537**, L127 (2000)
22. J. Sollerman et al. : Astron. Astrophys. **386**, 944 (2002)
23. R.A. Stathakis et al. : Mon. Not. R. Astron. Soc. **314**, 807 (2000)