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SN 1999E: another piece in the supernova–gamma-ray burst connection puzzle

L. Rigon,[1,2★] M. Turatto,[1] S. Benetti,[1] A. Pastorello,[1,2] E. Cappellaro,[3] I. Aretxaga,[4] O. Vega,[4] V. Chavushyan,[4] F. Patat,[5] I. J. Danziger[6] and M. Salvo[7]

[1]*Osservatorio Astronomico di Padova, INAF, Vicolo dell'Osservatorio 5, Padova, I-35122, Italy*
[2]*Dipartimento di Astronomia dell'Università di Padova, Vicolo dell'Osservatorio 3, Padova, I-35122, Italy*
[3]*Osservatorio Astronomico di Capodimonte, INAF, Via Moiariello 16, Napoli, I-80131, Italy*
[4]*Istituto Nacional de Astrofísica, Óptica y Electrónica, Aptdo Postal 51 y 216, Puebla, Mexico*
[5]*European Southern Observatory, Karl Schwarzschild Str. 2, D-85748, Garching bei München, Germany*
[6]*Osservatorio Astronomico di Trieste, INAF, Via G. B. Tiepolo 11, Trieste, I-34131, Italy*
[7]*Australian National University, Mt. Stromlo Observatory, Cotter Rd, 2611 Weston, ACT, Australia*

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ABSTRACT

Detailed optical and near-infrared observations of supernova (SN) 1999E have confirmed early suggestions that this supernova was indeed a twin of the peculiar type II SN 1997cy: it was exceptionally luminous and had evolved slowly, and the line profiles had narrow peaks and broad wings, indicating interaction with the circumstellar material. Nevertheless, the most intriguing characteristic was that, in analogy to SN 1997cy, it exploded at a position consistent in time and location with a BATSE event (GRB 980910). The a posteriori probability that the only two SNe with such an optical appearance are associated with two different BATSE gamma-ray bursts (GRBs) is only 0.2 per cent. This raises the possibility that some GRBs are associated with H-rich SNe.

Key words: supernovae: general – supernovae: individual: SN 1999E – supernovae: individual: SN 1997cy – gamma-rays: bursts.

1 INTRODUCTION

Core collapse supernovae (SNe), the final endpoints of massive star evolution, are usually considered to release approximately 10^{51} erg of kinetic energy. In recent years, however, a new perspective of explosions with a very different energy has emerged. On the one hand, SN 1997D was successfully modelled with an explosion energy of only 10^{50} erg (Turatto et al. 1998; Benetti et al. 2001; Chugai & Utrobin 2000; Zampieri et al. 2002), whereas on the other hand, SNe with explosion energies one order of magnitude larger than the average have been observed. To this class belong at least two objects associated (more or less closely) with gamma-ray bursts (GRBs), i.e the SNe 1998bw and 1997cy. Iwamoto et al. (1998) have dubbed supernovae with energy higher than 10^{52} erg as *hypernovae*, although the term is not universally adopted.

SN 1998bw was an unprecedented object, though with some similarity to SN 1997ef. Phenomenologically it was first classified as a type Ib supernova (Sadler et al. 1998) and later as a peculiar type Ic supernova (Filippenko 1998; Patat & Piemonte 1998). This latter classification was confirmed by the appearance of the nebular spectrum. Expansion velocities as high as 3×10^4 km s^{-1} and high luminosity (Patat et al. 2001) along with exceptionally strong radio emission with evidence of relativistic ejecta, made this object unique (Kulkarni et al. 1998). However, its most puzzling characteristic was the spatial and temporal association with the GRB 980425: this SN was discovered inside the 8-arcmin error box of the *BeppoSAX* WFC centred on the GRB, and the model of the early light curve indicates that the time of explosion was within $+0.7/-2$ d of the GRB detection (Iwamoto et al. 1998). The exceptional luminosity of SN 1998bw and the possible connection with the GRB (Iwamoto et al. 1998; Woosley, Eastman & Schmidt 1999) can be explained either by a hyper-energetic explosion or by a highly asymmetric emission (Höflich, Wheeler & Wang 1999). A comparative analysis between the data of SN 1997ef and those of SN 1998bw has highlighted significant similarities, although the former has a slightly smaller explosion energy, 8×10^{51} erg (Iwamoto et al. 2000). The recent SN 2002ap seems to lie at an even lower energy on the hypernovae sequence (Mazzali et al. 2002).

Also there is plausible evidence that a certain number of GRBs at high z are caused by SNe. Large deviations from the initial declines observed in the optical afterglows of some GRBs might indeed be caused by SNe. An interesting case is GRB 011201–SN 2001ke for which the afterglow optical spectra are consistent with the presence of a core-collapse SN shocking a dense circumstellar material (Garnavich et al. 2002).

★E-mail: turatto@pd.astro.it

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Another nearby object, SN 1997cy, was possibly associated with a GRB (Germany et al. 2000), with the uncertainty residing in the large error box of the BATSE detection. Indeed, this object showed an unprecedented photometric and spectroscopic behaviour: it was exceptionally luminous, possibly the most luminous SN ever detected, and slowly declining, while the spectra showed signs of ejecta–CSM interaction at all epochs (Turatto et al. 2000). The entire light curve has been reproduced by a model that requires the interaction of very energetic ejecta (3×10^{52} erg) of a 25-$M_{\odot}$ massive star with the CSM (with some contribution from radioactive decay).

In this paper, we report on the properties of SN 1999E, which showed many of the properties of SN 1997cy (Cappellaro, Turatto & Mazzali 1999; Filippenko et al. 1999b; Filippenko 2000). Indeed, in addition to a remarkable similarity in the optical domain, a loose but intriguing spatial and temporal coincidence with a GRB was noted by Thorsett & Hogg (1999): in the span between the discovery of this SN and the previous known observation of the parent galaxy (1998 July 29.046 UT), GRB 980910 was detected at a position spatially consistent with that of SN 1999E (separation of 4°.8 with a positional uncertainty $\sigma = 6°.8$ for the GRB).

2 SN 1999E

SN 1999E was discovered by Antezana on 1999 January 15 (Perez et al. 1999) 0.9-arcsec west and 10.0-arcsec south of the nucleus of an anonymous galaxy at RA $= 13^{\mathrm{h}}17^{\mathrm{m}}16^{\mathrm{s}}.37$, Dec. $= -18° 33' 13''.4$ (equinox 2000.0). The galaxy redshift is $z_{\mathrm{LSR}} = 0.0261$ ($\mu = 35.40$ adopting $H_0 = 65$ km s^{-1} Mpc^{-1}) as measured on the narrow peaks of the Balmer emission lines of the SN.

SN 1999E has been classified as a type IIn supernova owing to the presence of a strong and narrow Hα emission line (Filippenko et al. 1999a; Jha et al. 1999).

2.1 The light curves

Despite the unfavourable location of the SN upon a spiral arm, SN 1999E has been extensively observed in the optical (*UBVRI*) bands for over 450 d at different observatories (ESO La Silla: Dutch, Danish+DFOSC, 3.6+EFOSC2; La Palma: TNG; Mexico: OAN-Tonanzintla and OAGH-Cananea). The SN magnitudes were measured through a point spread function (PSF) fitting technique. In order to check for the amount of background contamination at late phases we derived the SN magnitudes on some frames with the template subtraction technique (see Fig. 1). The PSF technique seems to be adequate at least up to 200 d after discovery. However, in order to obtain a precise determination of the magnitudes at the latest phases, we subtracted from the SN images the reference frames of the parent galaxy taken 2.5 yr after the explosion, when the SN had faded. A few *JHK* observations are also available (ESO La Silla: NTT+SOFI). The V light curve and the $(B - V)$ colour curve are shown in Fig. 1. The object closely resembles the behaviour of type IIn SNe such as SN 1988Z (Turatto et al. 1993), with a slow luminosity decline and an almost constant colour.

The optical photometric data have been used to obtain the *UBVRI* 'bolometric' light curve, shown in Fig. 2. Infrared data have been excluded because they were available only over three nights. We have checked, however, that in all of these nights their contribution to the total (optical and infrared) luminosity was less than 10 per cent. In the same figure we also show the bolometric light curves of SNe 1997cy and 1998bw derived in the same way, for comparison.

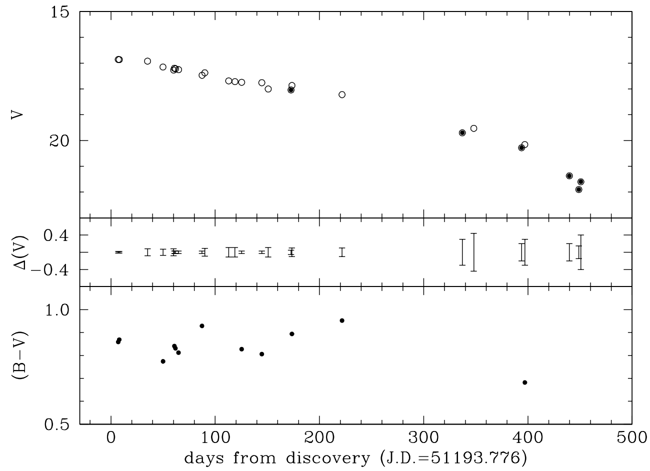

Figure 1. Top: V light curve of SN 1999E. Open symbols represent measurements performed with the PSF fitting technique and filled symbols represent those performed with the background subtraction method. Middle: estimates of the errors of the photometry performed via artificial star experiments. Bottom: $(B - V)$ colour curve of SN 1999E.

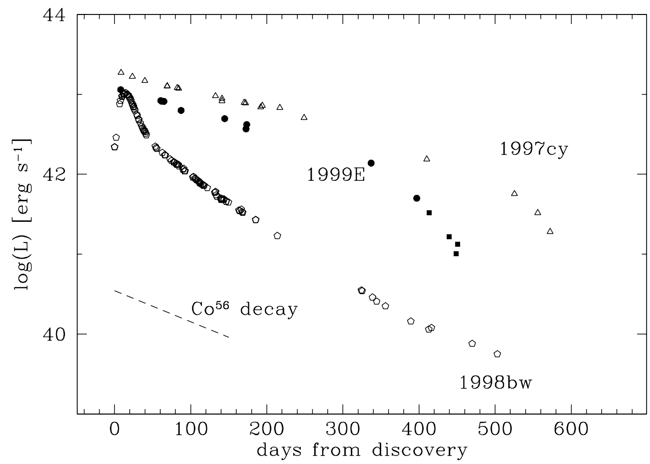

Figure 2. *UBVRI* bolometric light curve of SN 1999E compared with those of the hypernovae 1998bw (Patat et al. 2001) and 1997cy (Turatto et al. 2000). For each SN the luminosities are plotted versus the days from discovery. The last estimates have been scaled from the V magnitudes only. The dashed line corresponds to the ^{56}Co to ^{56}Fe decay rate, expected for full γ-ray trapping.

Because of the presence of significant interstellar absorption lines in the spectra, it is reasonable to expect SN 1999E to be significantly reddened. The EW of the NaID absorption lines originating in the parent galaxy, as measured in the higher-resolution spectra and signal-to-noise ratio, is approximately twice as strong as the Galactic component. Assuming that the gas-to-dust ratio inside the parent galaxy is the same as that in the Galaxy, we have adopted for the SN 1999E a total absorption $A_{B,\mathrm{total}} = 1.14$ mag, as the sum of $A_{B,\mathrm{MW}} = 0.38$ (Schlegel, Finkbeiner & Davis 1998) and $A_{B,\mathrm{host}} = 2 \times A_{B,\mathrm{MW}}$. With such an absorption value the absolute magnitude becomes $M_V < -19.5$, even ignoring the uncertain early magnitudes reported in the IAU Circulars.

Whatever the absorption suffered by SN 1999E is, the bolometric light-curve shape differs from those of other type II SNe: it does not show (at least up to approximately 400 d after the discovery) the radioactive tail owing to ^{56}Co, which characterizes normal type II SNe after 100 d from explosion. By comparison with SN 1987A, the bolometric light curve provides an upper limit to the ^{56}Co mass of approximately $1\,M_{\odot}$. However, by analogy with other type IIn SNe, e.g. SNe 1988Z (Turatto et al. 1993; Aretxaga et al. 1999) and 1995G (Pastorello et al. 2002), it is natural to attribute the slow decline of the light curve to interaction with a dense CSM. In particular, the light curve of SN 1999E appears to be very similar to that of SN 1997cy. Like the latter, SN 1999E is a very energetic supernova, with an explosion luminosity a few days after discovery exceeding 10^{43} erg s^{-1}. The luminosity of SN 1997cy was even higher (1.86×10^{43} erg s^{-1}), although it should be noted that for both SNe the epochs of maxima were not well known.

2.2 The spectrum

Spectra of SN 1999E at different epochs have been obtained at ESO La Silla (1.5 m + B&C, 3.6 m + EF2) and La Palma (WHT+ISIS) (see Fig. 3). The spectra show very broad features indicating very high expansion velocities, and the similarity with SN 1997cy is striking. This is illustrated in Fig. 4 where the spectra of the two

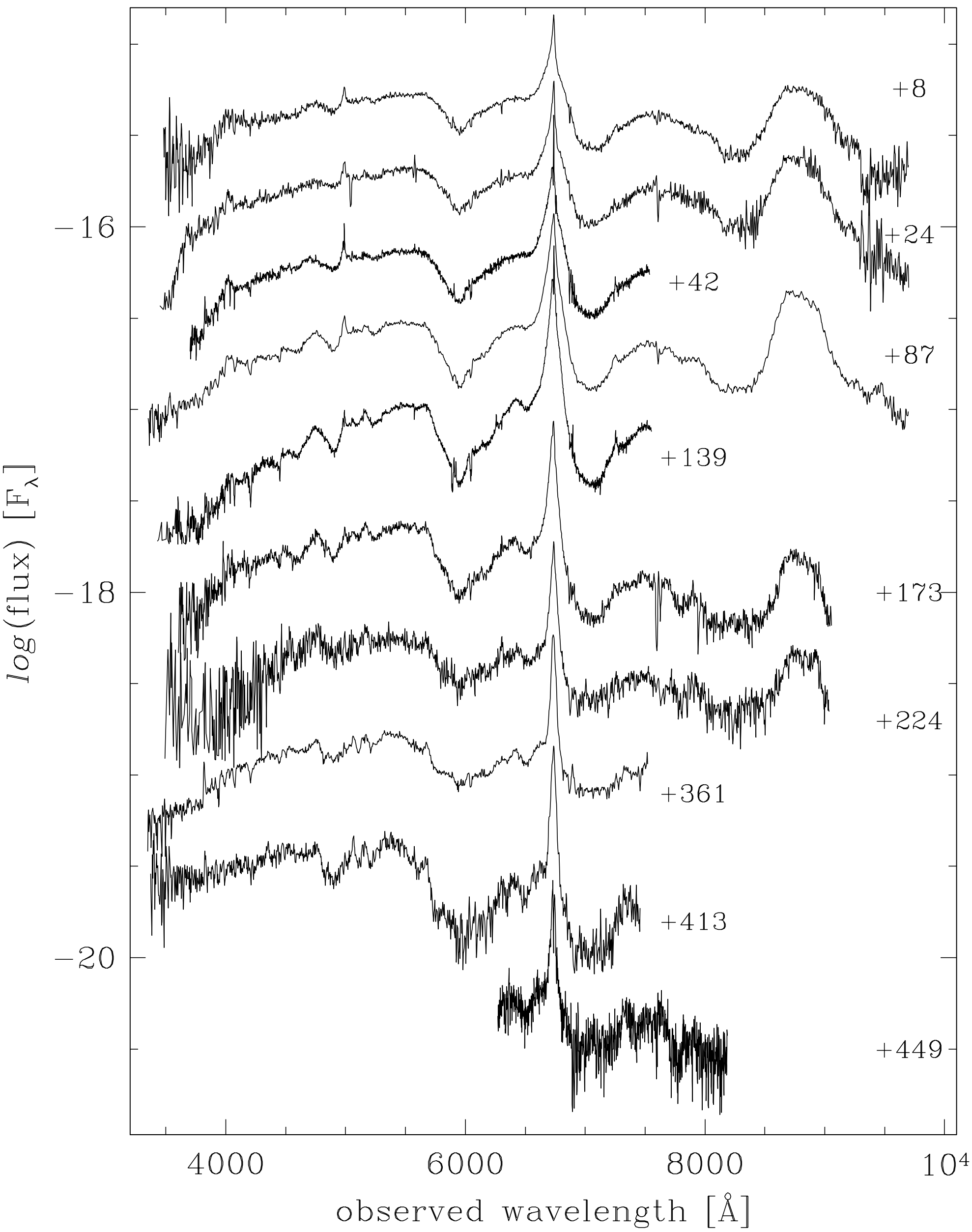

Figure 3. Spectral evolution of SN 1999E. The ordinate refers to the first spectrum, and the others have been arbitrarily shifted. The phase (days) is from the discovery date (1999 January 15). The spectra shown have been obtained with the following instruments: phase +8 d, Danish 1.5-m telescope at La Silla + DFOSC, resolution 12 Å; +24 d, ESO 1.5 + B&C, res. 15 Å; +42 d, William Hershel telescope at La Palma +ISIS, res. 3.1 Å; +87 d, ESO 3.6 m + EFOSC2, res. 17 Å; +139 d, ISIS, res. 3.1 Å; +173 d, DFOSC, res. 12 Å; +224 d, DFOSC, res. 12 Å; +361 d, EFOSC2, res. 18 Å; +413 d, EFOSC2, res. 18 Å; + 449 d, EFOSC2, res. 6.5 Å.

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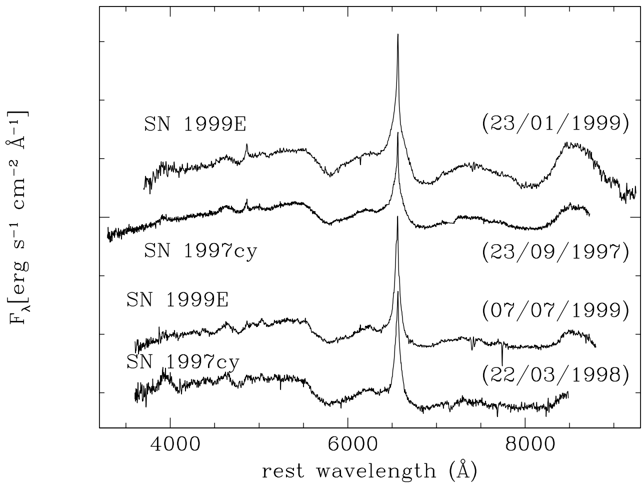

Figure 4. Comparison of the spectra of SN 1999E and SN 1997cy, corrected to the parent galaxy rest frames. The two spectra at the top have been obtained approximately 135 d past the GRB to which the SNe are possibly associated (+8 d past discovery for SN 1999E); those at the bottom approximately 300 d (+173 past discovery for SN 1999E). The ordinate scale refers to the top spectrum of SN 1999E, other spectra have been arbitrarily downshifted. The bottom two spectra have also been multiplied by a factor of 2 for an easier comparison.

SNe at two different epochs are compared. Even though evolution is slow, remarkably enough, the best correspondence between the two SNe is obtained by computing the phase from the respective GRB.

Fig. 5 shows the evolution of the Hα profile of SN 1999E, on the basis of our higher-resolution spectra. When the resolution is better than 4 Å (FWHM), a narrow P-Cygni profile can be detected above the broad emission. An underlying H II region, which could not be properly subtracted at the last two epochs (note the residual emissions of [N II], [S II] and Hα on July 20), contributes to the unresolved emission. However, the intensity of the narrow emission

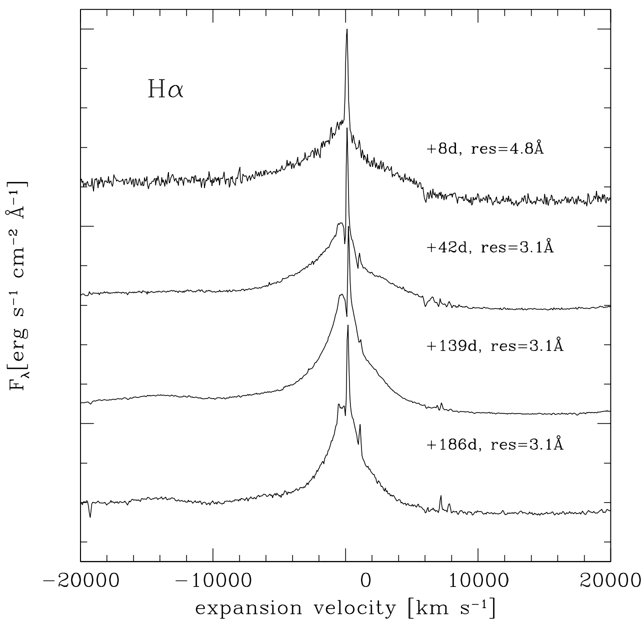

Figure 5. Time evolution of the Hα profile from the higher-resolution spectra. The line fluxes have been normalized to the peak intensities. Broad wings and narrow unresolved emissions and absorptions are visible.

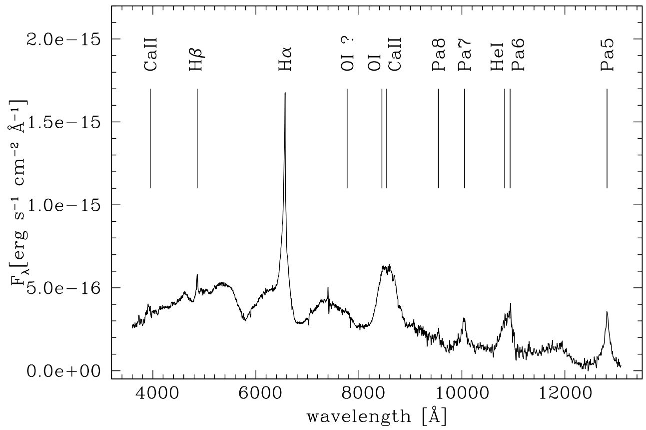

Figure 6. Line identifications in the optical-IR spectrum of SN 1999E (taken on 1999 March 11 with 1.5 m + B&C, phase +55 d, and 1999 March 7 with NTT+Sofi, phase +51 d) shifted to the rest frame of the host galaxy.

line decreases with time, indicating the presence of a component associated with the SN.

As in other type IIn SNe, e.g. SNe 1988Z (Turatto et al. 1993), a good fit to the Hα line profiles requires at least three components. At the first epoch (1999 January 23) the three components have Gaussian profiles with FWHM = 8600, 1900 and 200 km s^{-1}, respectively. The presence of P-Cygni profiles indicates the existence of a dense, slow-moving wind around the exploding star, such as in other type IIn SNe, e.g. SNe 1997ab (v = 180 km s^{-1}, Salamanca et al. 1998) and 1995G (v = 900 km s^{-1}, Pastorello et al. 2002). The positions of the absorption minima in SN 1999E indicate an expansion velocity of this shell of approximately 200 km s^{-1}.

Line identifications in the spectra of SNe with high expansion velocities are difficult. An attempt was made for SN 1999E by Filippenko (2000) in the optical spectra from the first months of observation. In Fig. 6 we identify the major lines in the optical–near-infrared (NIR) spectrum of SN 1999E on 1999 March. Balmer and Paschen lines of hydrogen are clearly detected: the Paschen lines show the same multicomponent structure as the Balmer ones. Also the Ca II IR triplet and H and K are clearly visible. O I 8446 Å is identified on the blue wing of the Ca II IR triplet and O I 7774 Å is also possibly detected. The Pa 6 line is blended with He 10 830 Å.

3 SN 1999E AND GRB 980910

The possibility that some gamma-ray bursts are associated with SN explosions has been suggested in recent years with the discovery of a handful of noteworthy temporal and spatial coincidences between GRBs and SNe, e.g. GRB 980425/SN 1998bw (Galama et al. 1998), GRB 970514/SN 1997cy (Germany et al. 2000), GRB 971115/SN 1997ef (Wang & Wheeler 1998) and GRB 011121/SN 2001ke (Bloom et al. 2002; Garnavich et al. 2002; Price et al. 2002).

SN 1999E can be added to this list. Thorsett & Hogg (1999) noted that GRB 980910 (BATSE trigger no 7077) was detected only 4$^\circ\!\!.$8 (corresponding to 0.73σ) from the SN location in the time interval elapsed between the discovery and the last pre-SN image of the host galaxy. Telemetry gaps prevented the inclusion of this burst in the flux and duration tables (Meegan C., private communication 2002). In that 172-d time interval there were 98 GRBs recorded in the BATSE GRB catalogue,[1] including both overwrite and overwritten events (Paciesas et al. 1999). Among these, GRB 980910 is the one closest to the SN 1999E location. Another burst, GRB 980920, with a much larger error box ($1\sigma = 9\overset{\circ}{.}98$), lies at approximately 1.2σ.

The probability of a chance association of SN 1999E with one of the 98 GRBs at a $0.73\sigma_i$ distance is 9.6 per cent, where σ_i is the corresponding error circle of each GRB (see Wang & Wheeler 1998; Germany et al. 2000). The same computation was performed for SN 1997cy. During the 126 d elapsed between the discovery of SN 1997cy and the previous image of the host galaxy that does not show trace of the SN, 125 GRBs were detected. GRB 970514, at 0.23σ distance from the SN location ($1\sigma = 3\overset{\circ}{.}8$), was the closest. The probability of a chance association at a $0.23\sigma_i$ distance from SN 1997cy is only 1.8 per cent.

From the probability computed above it appears that the association GRB 980910/SN 1999E is less stringent than for SN 1997cy. However, in the previous sections we have noted the striking similarities in luminosity and spectral evolution between SN 1999E and SN 1997cy. To the best of our knowledge, no other SNe observed so far have shared the same properties as these two objects. Therefore, one might argue in favour of a direct relation between those SNe with such optical features and γ-ray emission.

If we combine the probability of association of both SNe with their respective GRBs, we end up with only a 0.2 per cent probability of a chance association. Although we are aware of the caveats on a posteriori statistics, formally there is a 99.8 per cent probability of a causal link between SNe such as SN 1997cy and SN 1999E, and some kinds of GRBs.

4 CONCLUSIONS

SN 1999E was an intrinsically luminous ($M_V < -19.5$) type II SN. The light curve, flatter than the ^{56}Co decline during the first 400 d, requires an additional source of luminous energy, most likely resulting from the interaction with a dense CSM. The CSM signature can be read in the narrow (<200 km s^{-1}) P-Cygni profile detected in our highest-resolution spectra. The colour evolution of the SN also differs from that of normal type II SN, which soon after the maximum undergoes a phase of cooling (and reddening) owing to expansion (cf. Patat et al. 1994). Indeed, the spectra also show prominent lines without the characteristic P-Cygni profile and with broad wings (see Fig. 3), as in other type IIn SNe.

The most intriguing features of SN 1999E are its possible association with GRB 980910 and its striking similarity to SN 1997cy, also associated with a GRB. In Section 3 we have argued that the probability of a chance association of these two SNe with GRBs is low. We have also found that a remarkable correspondence between the spectral evolutions of the two SNe can be found if the phases are computed from the epoch of the GRB (cf. Fig. 4).

The epoch of explosion of SN 1999E is not known and is poorly constrained (Perez et al. 1999) as is that of SN 1997cy. It is natural to compare the light curves of these two SNe, taking the GRB trigger times as the epoch of the explosions. The result of this comparison is shown in Fig. 7: up to day 460 after the GRBs there is substantially no distinction between both energetics and time evolution of SN 1997cy and SN 1999E! After that epoch, SN 1999E starts a fast decline, while for SN 1997cy this occurs 100 d later.

[1] http://www.batse.msfc.nasa.gov/batse/grb/catalog/

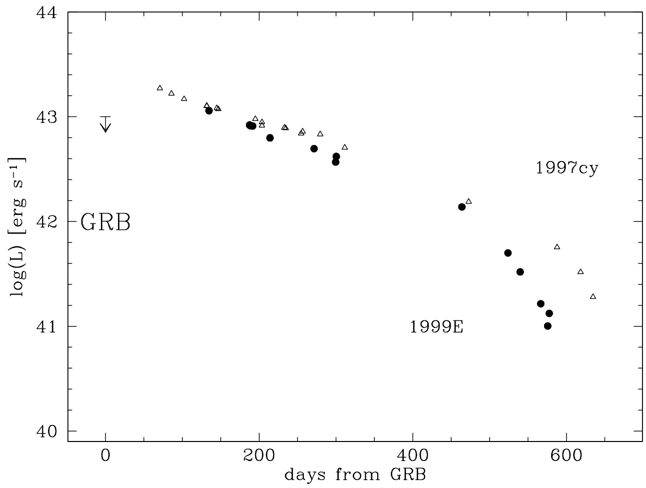

Figure 7. Comparison of the *UBVRI* bolometric light curve of SN 1999E with that of SN 1997cy when the phase is computed from the respective GRB.

The observations of SN 1999E seem, therefore, to support the conclusions drawn from SN 1997cy that these SNe are very energetic ($E_{\rm tot} \sim 10^{52}$ erg s) and may have massive progenitors (Turatto et al. 2000). The superposition of both SNe on spiral arms of their respective host galaxies is consistent with this conclusion. The forbidden lines typical of the late time spectra of core collapse SNe are not seen in the spectra of SN 1999E, even in those obtained more than 1 yr after the discovery, probably overwhelmed by emission owing to the ejecta–CSM interaction. The simple detection of the O I lines, obtained thanks to the high signal-to-noise ratio reached in the observations of SN 1999E (cf. Section 2.2 and Filippenko 2000), cannot tell us much concerning oxygen production in the explosion, nor whether any has been drawn into black hole formation. In fact, the oxygen producing this line may well be that which existed in the envelope of the progenitor star. The interaction of the SN ejecta with a dense CSM powers the light curves up to 460 (SN 1999E) and 580 (SN 1997cy) d after the burst. The difference in the subsequent drop in luminosity is possibly caused by different density distributions of the CSM.

The close similarity of the two events, both in terms of optical SN and the coincidence of γ-ray bursts, supports the hypothesis that this kind of energetic SNe may be associated with some specific type of GRB. Unfortunately, little is known concerning GRB 980910 (Section 3). In contrast, we do know that GRB 970514, associated to SN 1997cy, was of short duration (~0.2 s) and the total energy emitted was $\sim 10^4$ times less than that of other bursts with a measured redshift (Germany et al. 2000). The collapsar model explains the properties of the GRBs with long duration through the collapse of massive stellar cores into black holes (Woosley, Zhang & Heger 2002) but does not account for bursts as short as GRB 970514. This model requires the core to be massive enough to form a black hole and with a large angular momentum that forms a disc. It also requires the H and He envelopes of the star to have been stripped long before the explosion. This is not the case for SN 1999E and SN 1997cy, for which there is evidence of a dense, low-velocity shell of H-rich gas associated with the SN.

The supranova model (Vietri & Stella 1998), based on the delayed implosion of a rotating neutron star into a black hole, associates GRB with SNe from massive stars. In this scenario the SN explosion take place months or years before the GRB because the SN remains optically thick to γ-rays for several months. Because of the negative observations available for the two SNe approximately 2 months before the GRB, only a small temporal window for the explosions is available. This might be too tight a constraint.

Despite there not being a straightforward explanation for the explosions of SN 1999E and SN 1997cy within the current theoretical models, we find the possibility of an association between these H-rich, high-energy, CSM-interacting SNe with some GRB attractive.

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