SN1997cy/GRB970514 — A New Piece in the GRB Puzzle?

Lisa M. Germany; lisa@mso.anu.edu.au
Research School of Astronomy and Astrophysics, The Australian National University,
Private Bag, Weston Creek P.O., ACT 2611, Australia

David. J. Reiss; reiss@astro.washington.edu
Department of Astronomy, University of Washington,
Box 351580, Seattle, WA 98195-1580

Elaine. M. Sadler; EMS@Physics.usyd.edu.au
School of Physics, University of Sydney,
NSW 2006, Australia

Brian P. Schmidt; brian@mso.anu.edu.au
Research School of Astronomy and Astrophysics, The Australian National University,
Private Bag, Weston Creek P.O., ACT 2611, Australia

C. W. Stubbs; stubbs@astro.washington.edu
Department of Astronomy, University of Washington,
Box 351580, Seattle, WA 98195-1580

ABSTRACT

We present observations of SN 1997cy, a supernova (SN) discovered as part of the Mount Stromlo Abell Cluster SN Search (Reiss et al. 1998), which does not easily fit into the traditional classification scheme for supernovae. This object’s extraordinary optical properties and coincidence with GRB970514, a short duration gamma ray burst (GRB), suggest a second case, after SN 1998bw/GRB980425, for a SN–GRB association. SN 1997cy is among the most luminous SNe yet discovered ($M_R << -20.3$, $H_0 = 65$), and has a peculiar spectrum. We present evidence that SN 1997cy ejected approximately $2.6M_\odot$ of $^{56}$Ni, supported by its late-time light curve, and FeII/[FeIII] lines in its spectrum, although it is possible that both these observations can be explained via circumstellar interaction. While SN 1998bw and SN 1997cy appear to be very different objects with respect to both their gamma ray and optical properties, SN 1997cy and the optical transient (OT) associated with GRB970508 have roughly similar late-time optical behavior. This similarity may indicate that the late-time optical output of these two intrinsically bright
transient events have a common physical process. Although the connection between GRB970514 and SN 1997cy is suggestive, it is not conclusive. However, if this association is real, followup of short duration GRBs detected with BATSE or HETE2 should reveal objects similar to SN1997cy.

Subject headings: supernovae: general supernovae: individual: SN 1997cy, SN 1998bw — gamma rays: bursts, GRB970514, GRB970508, GRB980425

1. Introduction

Gamma Ray Bursts (GRBs) are among the most energetic and enigmatic phenomena studied in astronomy. The discovery of optical transients in association with these events (van Paradijs et al. 1997; Bond 1997), and the evidence of their cosmological origin (Metzger et al. 1997; Kulkarni et al. 1998; Djorgovski et al. 1998) have demonstrated the enormous energies involved with these intriguing objects. However, the association of GRB980425 with SN 1998bw has turned the subject on its head. SN 1998bw, located at z=0.0085 (Tinney et al. 1998), is the nearest GRB yet optically identified by a factor of 100, and is intrinsically fainter than previous GRB optical transients by several orders of magnitude. Its photometric and spectral resemblance to a type Ic SN, objects which are thought to result from the core collapse of massive stars whose outer envelopes have been stripped away either by binary interaction or a stellar wind, indicates that at least some GRBs are associated with this type of event. However, does this object represent the same physical situation as the optical counterparts to the more distant GRBs which are on the order of $10^5$ times brighter?

The coincidence of GRB980425 with a peculiar SN suggests that other such associations are likely. Unfortunately, the statistics are not usually compelling for singling out individual objects due to the large numbers of GRBs and their poor positional information. Wang & Wheeler (1998) have cross-correlated the SN and Burst and Transient Source Experiment (BATSE) catalogs and have identified a positive correlation with SN Ic. However, Kippen et al. (1998) have used a more sophisticated error model for the BATSE data and found no correlation. Woosley, Eastman, & Schmidt (1998) took a different approach and looked for GRB associations for three SNe, SN 1992ar, SN 1997cy and SN 1997ef, which exhibit the high luminosity and peculiar spectra displayed by SN 1998bw. Of these three objects, only SN 1997cy, presents a compelling case for a second SN/GRB association.

In this paper, we detail the spectroscopic and photometric properties of SN 1997cy. We present the optical discovery and follow up observations in section 2, we provide evidence
that GRB980514 is associated with SN 1997cy in Section 3, and in section 4, we explore the properties of the GRB/SN.

2. Photometric Observations

SN 1997cy was discovered on CCD images taken 1997 July 16 (Germany et al. 1997) as part of the Mount Stromlo Abell Cluster Supernova Search (Reiss et al. 1998). The SN occurred in an anonymous, faint $(M_V = -17.7$ within a 8 kpc radius, $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$), blue $(V - R = 0.1 \pm 0.1)$, low surface brightness galaxy near Abell Cluster 3266 (Abell, Corwin, & Olowin 1989) at a redshift of $z = 0.063$ (cluster redshift $z = 0.059$; Teague, Carter, & Gray 1990). The SN’s position at $\alpha = 4^h32^m54.81^s$, $\delta = -61^\circ42'57.9''$ (J2000) is offset from the centre of its host galaxy by 0.9'' E and 1.4'' N. Unfortunately, the discovery image was the first of the observing season and the most recent pre-discovery image, where the SN is not present, was taken ~4 months earlier on 1997 March 12. Therefore the date of explosion is not well constrained.

The first spectrum of SN 1997cy was obtained on 1997 July 24 with the Danish 1.5m telescope in the wavelength range 3200 - 8800 Å at a resolution of 20 Å (Benetti, Pizzella, & Wheatley 1997). We obtained two further spectra on 1997 August 9 and 1998 June 26 with the Mount Stromlo and Siding Spring Observatory’s (MSSSO) 2.3m telescope. These later spectra encompass a wavelength range of 3900 - 7500 Å at a resolution of 4.4 Å, were wavelength calibrated using observations of a Cu-He lamp taken at the position of the SN, and flux calibrated using sensitivity curves determined from the observation of southern flux standards chosen from the list of Bessell (1999).

We monitored SN 1997cy photometrically in the MACHO $V_M$ and $R_M$ passbands (Stubbs et al. 1993; Bessell & Germany 1999) on the MSSSO 1.3m telescope, and in the $BV(RI)_{KC}$ system with the MSSSO 2.3m telescope for 15 months. Additional photometric and spectroscopic observations have been taken at European Southern Observatory and will be published separately (Turatto et al. 1999).

In order to properly determine a SN magnitude from a CCD frame, one must first remove the light from the host galaxy. We accomplish this by subtracting from each observation a template image where the SN is not present. We construct template images for the data taken with the MSSSO 1.3m telescope from $V_M$ and $R_M$ images obtained in good seeing conditions (1.4'') on 1997 January 2. Using the techniques described in Reiss et al. (1998), we register each of the images containing the SN to the appropriate template image, convolve the point spread function (PSF) of the stars in the template with a kernel
to match the PSF of the stars in the registered images, then match the flux in the registered images and the template. We then subtract this intensity-transformed, convolved template from each registered observation. Once we have removed the light of the host galaxy, we calculate the relative photometry between the SN and a number of local comparison stars through PSF fitting with DoPHOT (Schechter, Mateo, & Saha 1993). This process is detailed in Schmidt et al. (1998).

We can not apply the above techniques for extracting SN magnitudes to the $BV$($RI$)$_{KC}$ MSSSO 2.3m data, because SN 1997cy is still visible and no template yet exists in these bandpasses. However, it is possible to obtain photometry for these images at early times since the SN is so much brighter than its host galaxy. To measure the magnitude of the SN, we use the IRAF task PHOT to obtain differential photometry, within a 3" aperture, between the SN and the local comparison stars, and apply a correction for the galaxy brightness. We calculate the galaxy-correction for each filter (ranging in size from 0.2 - 0.4 mag for $B$, 0.1 - 0.3 mag for $V$, and 0.1 - 0.2 mag for $R_{KC}$ and $I_{KC}$) based on the galaxy magnitude. This magnitude is derived from the MSSSO 1.3m $V_M$ and $R_M$ template images within this same 3" aperture and corrected to $BV$($RI$)$_{KC}$ using the $V_M$ and $R_M$ transformations calculated by Bessell & Germany (1999).

We put the local comparison stars onto the $BV$($RI$)$_{KC}$ standard system under photometric conditions obtained with the Cerro-Tololo Interamerican Observatory (CTIO) 1.5m on 1999 February 18 and 1999 March 9 and the CTIO 0.9m on 1999 February 28. We determined the transformation coefficients to the $BV$($RI$)$_{KC}$ standard system and the airmass coefficients for each night from observations of multiple Landolt fields (Landolt 1992) taken over a wide range of airmasses. We measured PSF magnitudes for the standard stars and local comparison stars using DAOPHOT (Stetson 1987) and give the standard magnitudes for the comparison stars in Table 1. The statistical uncertainties in the measurements are included in parentheses.

We cannot calibrate the local comparison stars in the $V_M$ and $R_M$ system in the same way since no record is kept as to whether or not conditions are photometric. However, Bessell & Germany (1999) have determined transformation equations to convert the magnitudes of normal giant stars in the $BV$($RI$)$_{KC}$ standard system to the $V_M$ and $R_M$ system. These transformations are:

$$V_M = 0.153(B - V) + V$$  \hspace{1cm} (1)

$$R_M = -0.154(V - I) + R$$  \hspace{1cm} (2)

We apply Equations 1 and 2 to the photometry of the local comparison stars in the $BV$($RI$)$_{KC}$ system to calculate their magnitudes in the $V_M$ and $R_M$ system. We then
determine the magnitude of the SN in each of the images from the MSSSO 1.3m from the relative photometry between the SN and the calibrated local standards shown in Figure 1 and Table 1.

SN 1997cy is at \( z = 0.063 \) and k-corrections are not negligible for this object. Unfortunately, the peculiar nature of SN 1997cy precludes the use of other SNe for calculating k-corrections, and we have based our corrections on the spectra presented here, which have been extrapolated as necessary. Since the corrections for \( V_M \) to \( V(z=0) \) and \( R_M \) to \( R_{KC}^{(z=0)} \) are an order of magnitude larger than correcting \( V \) and \( R_{KC} \) to \( z = 0 \), we add constants to the \( V_M \) and \( R_M \) data to bring them into alignment with the k-corrected \( V \) and \( R_{KC} \) data respectively. SN 1997cy is a unique event without good spectrophotometry, and therefore these k-corrections are uncertain and estimated to be about as good as their size, \( \sim 0.15 \text{ mag} \). Due to the extreme luminosity of this object, however, the uncertainty in the k-corrections has little effect on our conclusions. Table 2 and Table 3 summarize the photometry and k-corrected photometry obtained for SN 1997cy, and Figure 2 shows the light curves. The \( V \) and \( R_{KC} \) light curves are well sampled by the \( V_M \) and \( R_M \) observations taken on MSSSO 1.3m.

3. Is SN 1997cy GRB970514?

From the optical data, it is unclear exactly when SN 1997cy exploded, but it was certainly sometime between 1997 March 12 and 1997 July 15, based on the discovery and pre-discovery images. During this 4 month period, 119 BATSE events were detected (Brainerd 1999), two of which overlapped SN 1997cy’s position within 2\( \sigma \). These were GRB970403 (1.92\( \sigma \), 17.3° from SN) and GRB970514 (0.23\( \sigma \), 0.88° from SN). GRB970514’s proximity is clearly unexpected — it is the closest event to SN 1997cy’s position yet detected by BATSE (April 1991 through May 1999) by a factor of 2.5. Using the prescription of Wang & Wheeler (1998), the probability that a 0.23\( \sigma \) event will occur randomly given the 119 BATSE events and their respective error circles, is 1.7% — an unlikely occurrence. The fact that two objects are found within a 2\( \sigma \) radius, however, is not surprising. Over this time-frame with the 119 events observed, \( 2 \pm 1.5 \) random coincidences of this significance are expected.

GRB970514 had a smaller error circle (3.7°) than a typical BATSE burst, and the

\[ p = 1 - \prod_{i=1}^{N} \left( 1 - \left( \frac{\pi (0.23\sigma)^2}{4\pi} \right) \right), \]

where \( \sigma_i \) is the 1\( \sigma \) BATSE error circle for each object measured in radians. We note that this approximation assumes that none of the error circles overlap — a reasonable approximation in this situation.
above calculation provides the probability of a chance association between all bursts and SN 1997cy, regardless of their uncertainty. Unfortunately, BATSE error circles span a wide range of sizes. Just three objects contain over 30% of the probability for chance association and more than half of the probability of coincidence is contained in only 10% of the most poorly determined positions. With this approach, if SN 1997cy had been 5° (0.23σ) away from GRB970627 (21.9° error circle), the likelihood of a chance coincidence would be the same as what was calculated above (1.7%). A different approach is to ask, given 119 events, what is the probability that one will fall within 0.88°. This is the method we would use if we had no error model information, and is equivalent to assigning all 119 BATSE events error circles of 3.7°. A calculation analogous to that above shows that the probability of a chance 0.88° association of the SN and 119 BATSE events is 0.7% (a 5° coincidence would have a 20% probability with this method).

As a sanity check, we cross-correlated the entire BATSE (up through 1999) catalog with the 677 SNe discovered from 1991 to 1999 (Cappellaro 1999) and looked for SNe which had a GRB burst closer than 1° within 121 days of discovery. Apart from SN 1997cy, 5 objects emerge, in agreement with the expected number of chance coincidences, 4.5 ± 2.5, for this data set. Of these 5 objects with coincidences, two are SN II (SN 1992Z, SN 1992aw) whose spectra were not noted as being peculiar, two are normal SN Ia (SN 1996av, SN 1996bx), and the final object is SN 1993J, whose time of explosion is well known and does not match that of the correlated GRB. We conclude that there are no other SN/GRB coincidences as compelling as SN 1997cy/GRB970514.

We have taken a conservative approach in deriving the above likelihoods of a chance coincidence between GRB970514 and SN 1997cy that does not take into account the slow spectral and photometric evolution of SN 1997cy (which suggest it was more than a month old at discovery). If this were to be taken into consideration, the chance of a random coincidence decreases further. However, despite this conservatism, we are still subject to the vagaries of a posteriori statistics because we have had to specify an interesting SN/GRB angular separation — after the fact. If, for example, we had chosen a 1 − σ error circle, rather than the 0.23 − σ error circle (as was found to be interesting in this case), the chance for a coincidence between SN 1997cy and a GRB is 15%. So although a chance correlation between GRB970514 and SN 1997cy is unlikely — about 100 to 1, it is still possible. We emphasize that we sought a GRB coincidence initially only for this object given its extreme nature, and while we believe the association is compelling, it is certainly not conclusive. We proceed making the reasonable assumption that SN 1997cy is indeed GRB970514.
4. Properties of GRB970514 and SN 1997cy

4.1. GRB970514

GRB970514 was detected on 1997 May 14, with BATSE on board the Compton Gamma Ray Observatory. The BATSE burst profile indicated that GRB970514 was a member of the Fast Rise Exponential Decay subclass of single peak events and had a duration of $\sim 0.2s$. The total gamma-ray fluence over all channels was $(4.1 \pm 1.3) \times 10^{-7}$ ergs cm$^{-2}$, a factor of 10 less than that of GRB980425. If we assume that GRB970514 is at the redshift of SN 1997cy and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$), this fluence translates into an estimated burst energy of $\sim 4 \times 10^{48}$ ergs. This is more energy than GRB980425 released (Galama et al. 1998) but $\sim 10^4$ times less than other bursts with measured redshifts. Emission was detected above 300keV marking it as a high-energy (HE) burst (Pendleton et al. 1997). These properties set GRB970514 apart from all other GRBs which have had an identified optical transient.

Given the association of GRB980425 with SN 1998bw, Bloom et al. (1998) and Norris, Bonnell, & Watanabe (1998) have proposed a SN associated subclass of GRBs (S-GRBs), based on the properties of GRB980425. These S-GRBs have a simple, broad burst profile with a rounded maximum, no high energy (NHE) emission, no long-lived X-ray afterglow and prompt radio emission. In contrast, GRB970514 contains HE emission and displays a cusp rather than a rounded maximum. Unfortunately there was no immediate radio or X-ray followup of GRB970514 and no definite properties that can be assigned to a S-GRB subclass have emerged from these two objects.

4.2. Spectra of SN 1997cy

Figure 3 shows a spectrum of SN 1997cy obtained with the MSSSO 2.3m telescope on 1997 August 9, 87 days after GRB970514. Also plotted are MSSSO 2.3m spectra of SN 1998bw which bracket the age of SN 1997cy, and a spectrum of SN 1991T, a type Ia SN approximately 85 days after explosion (Phillips et al. 1992). It is clear from these spectra that the two objects found to be associated with GRBs are very different. SN 1998bw is classified as a type Ic SN (Patat & Piemonte 1998) due to the absence of Si, H and He lines which are representative of type Ia, type II and type Ib SNe respectively. SN 1997cy appears to be a hybrid object, containing the H lines present in type II SNe as well as

\footnote{\textit{However, late time observations with the Australia Telescope Compact Array were obtained and are discussed in Section 4.4.}}
FeII/[FeIII] lines found in late time spectra of type Ia SNe (Branch et al. 1983). Such an object cannot be classified under the conventional scheme, and is probably best referred to as a peculiar type II SN as per Benetti et al. (1997).

The dominant feature in the spectrum of SN 1997cy is an intense Hα emission line with broad (∼ 3000 km s\(^{-1}\)) and narrow (∼ 300 km s\(^{-1}\)) components. However, it lacks the P-Cygni profile of Hα normally found in type II SNe, and is reminiscent of the peculiar type IIn SN 1988Z (Stathakis & Sadler 1991; Turatto et al. 1993). This line profile suggests that a significant amount of interaction between SN 1997cy and the surrounding circumstellar material is taking place (Chugai 1991). The other main features near 4600 Å (∼ 10,500 km s\(^{-1}\)) and 5300 Å in SN 1997cy coincide with the position of [FeIII] typical of late time type Ia spectra.

The origin of the broad absorption feature extending from 5645 Å to 6115 Å and centred at 5795 Å is unclear. While He(5876) and Na D(5893) are possibilities, the absorption seems far too broad and centered at too low a velocity for this to make sense. Given the GRB connection, one might be tempted to consider that this absorption is Hα from a jet pointed towards our line of sight. However there is no comparable Hβ absorption. Another possibility is that this is not an absorption feature at all, but rather a region without emission lines.

Figure 4 shows a spectrum of SN 1997cy taken 408 days past GRB970514. Hα still dominates the spectrum although it appears narrower than in the spectrum taken 87 days after GRB970514. This and the continued presence of the mysterious dip at 5795 Å show the spectrum of SN 1997cy has not evolved significantly in almost a year.

More recently SN 1999E was found to have a spectrum similar to SN 1997cy. It displays an intense Hα emission line, a broad absorption feature centred near 5970 Å and broad undulations similar to SN 1997cy (Filippenko, Leonard, & Riess 1999; Jha et al. 1999; Cappellaro, Turatto, & Mazzali 1999). In addition, it was atypically luminous \( M_V < -19.4 \) \( (H_0 = 65 ; \) Jha et al. 1999\) and can be linked to GRB980910 (Thorsett & Hogg 1999), although without great certainty [There are no prediscovery images and this SN is separated by 4.8° from the GRB position - which itself is uncertain by 6.8°].

4.3. Interpreting the Light Curve of SN 1997cy

We have constructed a \( L_{UVOIR} \) light curve by integrating over the \( V_M, R_M \) and \( BV(RI)_{KC} \) photometry from the data taken 1997 August 9 and 10, before it was k-corrected. We derived the effective wavelengths and flux measurements for each filter by
convolving their filter transmission curves in the rest frame of the SN (Bessell 1990; Bessell & Germany 1999) with the absolute spectrophotometry of Vega (Dreiling & Bell 1980). In keeping with the observed properties of SN, we extended the IR with a Rayleigh Jeans tail and truncated the UV with a function that declined much faster than a black body. This treatment of the UV is to simulate line blanketing and represents a lower bound for the flux beyond the $B$ filter. The correction is reasonably secure since most of the flux of the SN is contained within the wavelengths we have observed; the total flux extrapolated to lie beyond the wavelength region of the observations is approximately 20%. We held this derived correction fixed (for lack of better information) for all observations and ascribed a systematic error equal in size to the correction (20%) in the $L_{UVOIR}$ light curve. We note that if SN 1997cy has a large UV or IR excess, then the derived bolometric luminosity could be underestimated.

Figure 5 shows the $L_{UVOIR}$ light curve of SN 1997cy compared to that of SN 1998bw (Woosley et al. 1998) and a simple model where the late time flux is solely due to the complete thermalization of gamma-rays from the decay of $2.6 M_\odot$ of $^{56}$Co. SN 1997cy was clearly much brighter than SN 1998bw and initially declined at the rate of $^{56}$Co. We believe the large excursion from the $^{56}$Co decay line is due to circumstellar interaction which has subsequently decayed. This picture is consistent with the presence of FeII/[FeIII] lines (the final decay product of $^{56}$Ni) and Hα in the spectrum (Chugai 1991). It is also possible that the SN is being powered only by circumstellar interaction, and the decay rate is only a coincidence. Nomoto et al. (1999) have modelled SN 1997cy’s light curve under this latter assumption and find they can reproduce this late-time behaviour with an extremely energetic ($8 \times 10^{52}$ erg) SN explosion expanding into dense circumstellar material. A clumpy circumstellar medium may allow a somewhat smaller explosion energy. Regardless of the cause, the energy output is large, with the integral of $L_{UVOIR}$ from discovery to 450 days later yielding $1.6 \times 10^{50}$ ergs.

SN 1997cy is unlike any other SN observed (except 1999E previously discussed), and its unusual nature and coincidence with GRB970514 prompts speculation as to whether it is a SN, or rather an optical transient associated with a GRB (GRBOT).

GRBOTs have been discovered previously (van Paradijs et al. 1997; Bond 1997), but none are short duration events, and only the GRBOT associated with GRB970508 (Bond 1997) has a convincing redshift ($z = 0.835$, Bloom et al. 1998) and a well sampled $R$ light curve from early to late times (Fruchter et al. 1999). In order to compare SN 1997cy to the GRBOT associated with GRB970508 we construct an equivalent $R$ light curve for SN 1997cy at $z = 0.835$ by calculating the flux distribution measured across the $V_M$, $R_M$ and $BV(RI)_{KC}$ passbands (as described above), and then redshifting this flux distribution
from $z = 0.063$ to $z = 0.835$. We scale the flux down by the square of the luminosity distances ($q_0 = 0.1$) and by another factor of $(1 + z)$ (to account for the $d\lambda$ change), extrapolating the data to near UV wavelengths for complete $z = 0.835$ $R$ band coverage. The $z = 0.835$ $R$ band magnitude is synthesized from this flux distribution and the offset between this and the observed $V_M$ magnitude is applied to all $V_M$ data to produce the $R$ light curve of SN 1997cy as it would have been observed at $z = 0.835$. The uncertainty in the $z = 0.835$ $R$ light curve is approximately 0.2 mag, and is dominated the UV flux extrapolation to cover the redshifted $R$ bandpass.

Figure 6 plots the $z = 0.835$ $R$ light curve for both SN 1997cy and the GRBOT970508 (Fruchter et al. 1999). The overlap region shows that the gross properties of the two late-time light curves are similar, with SN 1997cy outshining GRBOT970508 by about 1.7 mags. While it was earlier demonstrated that SN 1997cy is declining with a rate remarkably consistent with the 77 day half life of $^{56}\text{Co}$, a similar analysis of GRBOT970508’s late-time emission is inconclusive; the data are consistent with a 77 day half life, but are too poor to substantiate this hypothesis. However, the general agreement between these two light curves suggests that SN 1997cy and GRBOT970508 may share similar physical properties at late times. It may be worthwhile to investigate the late-time light curves of suitable GRBOTs and see if the radioactive decay of $^{56}\text{Co}$ to $^{56}\text{Fe}$ is responsible for their late-time energy output.

Because of the different properties between GRB970514 and all other GRBs with associated OTs, further comparison is dangerous. We note, however, that if SN 1997cy is a GRBOT with properties similar to those already discovered, then the disparity between the intrinsic fluences of its associated GRB and other GRBs (GRB970508 is 5000 times more luminous than GRB970514 given their respective redshifts of $z = 0.835$ and $z = 0.063$) is naturally explained by relativistic beaming, where distant GRBs are beamed towards us, but GRB970514 had no preferred orientation. This model demands that the relativistic beaming factor, $\gamma$, for GRBs is low, $\gamma < 10$. Larger values of $\gamma$ would make the chance of seeing any gamma rays from SN 1997cy impossibly small. This conclusion is only valid, however, if we assume that GRB970514 belongs to the same general class of objects which make up the observed GRBOTs – a dubious assumption.

The existence of SN 1998bw/GRB980425 complicates issues because it appears to be a very different object compared to SN 1997cy/GRB970514 with respect to both its GRB and SN properties, and because the optical properties of SN 1998bw are very different from other GRBOTs. If SN 1998bw and SN 1997cy are both GRBs, these two events, coupled with the significant number of GRBOTs identified at $z > 0.8$ (Djorgovski et al. 1998), provide strong argument for the luminosity function of GRBs to be either rapidly evolving,
bimodal or very broad. We prefer the latter two explanations since it is difficult to imagine how an astrophysical event can evolve by a factor of $10^4$ from $z = 1$ to $z = 0$. Bimodality is a natural consequence of a beaming model, but the significant difference between the two nearby SN/GRBs argues that GRBs could be produced by more than one mechanism. It is therefore quite possible, or even likely, that an observed bimodality of the GRB luminosity function could be a consequence of both beaming and a variety of explosion mechanisms which lead to GRBs.

### 4.4. Late Time Radio Observations of SN 1997cy

Radio continuum observations of the field of SN 1997cy were made with the 6A (6 km) configuration of the Australia Telescope Compact Array during a 14-hour session on September 15 1998. The telescope observed simultaneously in two bands, with central frequencies 1.384 GHz (20 cm band) and 2.496 GHz (13 cm band) and bandwidth 132 MHz. Data reduction was carried out in the usual way with the AIPS package. The synthesized beam FWHM was about 6.7 arcsec at 20 cm and 3.6 arcsec at 13 cm.

No radio emission from SN 1997cy was detected at either frequency, and the RMS noise in the final cleaned maps near the position of the SN was 78 $\mu$Jy/beam at 20 cm and 68 $\mu$Jy/beam at 13 cm. We therefore adopt $3\sigma$ upper limits to the radio flux density of SN 1997cy of 0.23 mJy at 20 cm and 0.20 mJy at 13 cm. At the distance of SN 1997cy, this corresponds to upper limits of $2.3 \times 10^{21}$ W/Hz and $2.0 \times 10^{21}$ W/Hz for the radio luminosity at 20 and 13 cm respectively.

Unfortunately, the upper limit of $2.3 \times 10^{21}$ W/Hz for the 20 cm radio luminosity of SN 1997cy is not very restrictive because the SN was so distant. The 20 cm radio luminosity of SN 1998bw (the most luminous radio SN yet discovered) reached a maximum of about $5 \times 10^{21}$ W/Hz, but only exceeded $2.3 \times 10^{21}$ W/Hz for a period of about forty days between 40 and 80 days after explosion (Kulkarni et al. 1998). The radio light curve of the next most luminous radio SN, the type II SN 1988Z (van Dyk et al. 1993), rose much more slowly, reaching a 20 cm luminosity of $1.8 \times 10^{21}$ W/Hz almost five years after explosion (at which point the 20 cm emission was still rising).

Our radio data, taken about 16 months after explosion, cannot rule out the possibility that SN 1997cy was as powerful as SN 1998bw (where the 20 cm peak was reached less than 50 days after explosion) or SN 1988Z (where the 20 cm flux density was still rising after almost five years). Another deep radio observation in 2-3 years time might set some further constraints on the late-time radio light curve of SN 1997cy, but unless this interesting SN is
an even more radio-luminous version of SN 1988Z we are unlikely ever to learn much more about its radio properties.

5. Conclusion

SN 1997cy is, to our knowledge, the brightest SN yet discovered \([M_R=-20.3 \ (H_0 = 65)\) at discovery, and certainly much brighter at maximum light]. Its extreme luminosity and peculiar type II spectrum suggest the progenitor was a supermassive star that underwent core collapse. In addition, SN 1997cy may claim the most prodigious output of \(^{56}\text{Ni}\) with our simple model indicating that it put out 30 times more \(^{56}\text{Ni}\) than is produced in typical core collapse SN. If instead the late-time light curve is solely due to energy input from circumstellar interaction, SN 1997cy is still a remarkable event, with an explosion energy considerably larger than \(10^{50}\) ergs. In either case, SN 1997cy is an excellent candidate for a black hole induced hypernova (Paczynski 1997; Iwamoto et al. 1998), collapsar (Woosley 1993; Woosley 1996), or possibly a pair production supernova (Woosley 1986), with the latter being the only model which can easily output as much as \(2.6 \, \text{M}_\odot\) of \(^{56}\text{Ni}\).

The levelling off of the light curve at late times and later reversion to the \(^{56}\text{Co}\) decay line is probably due to energy input from circumstellar interaction which started to diminish in its effect at approximately 300 days after explosion. This conclusion is supported by the the presence of a narrow and broad component to the H\(\alpha\), and the absence of H\(\alpha\) absorption (Chugai 1991). The material illuminated by this circumstellar interaction may pose problems for the clean environment necessary for some gamma-rays burst models, but provides the possibility that the X-ray pulse of the SN could be inverse compton scattered off the fast electrons formed as the first material from the SN and the surrounding material collide.

The association of SN 1997cy with GRB970514 is suggestive, but not conclusive. If this association is real there are two GRBs with measured redshifts below \(z < 0.1\) (Tinney et al. 1998; Benetti et al. 1997), and many more at \(z > 0.5\) (Djorgovski et al. 1998). Despite the obvious problems associated with such small numbers and the non-uniform way in which SNe are discovered, only a bimodal or very broad luminosity distribution can easily explain the observed distribution of these GRB redshifts. Bimodality naturally occurs within a beaming model, but it could be complicated by the existence of two or more populations of objects which give rise to GRBs. One thing is clear, if a non-negligible fraction of GRBs are SNe at \(z < 0.1\), these objects should be easily uncovered if BATSE LOCBURST events with \(< 2^\circ\) error circles are followed up using the new breed of wide-field imagers on small telescopes.
The search for optical transients associated with GRBs should intensify over the next few years given the small positional error circles achievable with BeppoSAX and HETE2, and the large swaths of sky that instruments such as the MSSSO 1.3m and other small telescopes can observe. Such optical followup of GRBs is necessary if we are to discover if SN/GRB associations like SN 1997cy/GRB970514 and SN 1998bw/GRB980425 are real, or pure chance. Only with more data can we learn how SNe fit into the big picture of GRBs.

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Fig. 1.— The field of SN 1997cy showing pre and post SN images of the galaxy and the positions of the field reference stars.

Fig. 2.— $BV(RI)_{KC}$ light curves of SN 1997cy shown with the decay rate of $^{56}$Co, k-corrected to $z = 0$.

Fig. 3.— Spectra of SN 1998bw taken 62 and 111 days after GRB980425, SN 1997cy taken 87 days after GRB970514 and SN 1991T at 85 days after explosion. SN 1997cy is a distinctly different object, but seems to have FeII/[FeIII] features in common with SN 1991T at a similar age, and a H$\alpha$ profile similar to those SNe thought to be undergoing circumstellar interaction.

Fig. 4.— A binned spectrum of SN 1997cy taken 408 days after GRB980514. The spectrum shows that the SN has evolved little in the year since its discovery.

Fig. 5.— Bolometric light curve of SN 1997cy compared to that of SN 1998bw and a simple model showing the production of 2.6 $M_\odot$ of $^{56}$Co. The error bar in the top corner represents a systematic error of 20%.

Fig. 6.— The $R$ light curve of the OT associated with GRB970508 compared to the $R$ light curve of SN 1997cy as it would appear at this same redshift. SN 1997cy is a factor of 3 brighter than this GRBOT970508, and exhibits a similar light curve behavior in the areas of overlap.
Table 1. Calibrated Magnitudes of Field Reference Stars

| Star | B        | V        | R        | I        |
|------|----------|----------|----------|----------|
| 1    | 18.387(0.017) | 17.907(0.011) | 17.607(0.017) | 17.275(0.024) |
| 2    | 19.506(0.030) | 18.406(0.012) | 17.747(0.019) | 17.151(0.028) |
| 3    | 18.943(0.188) | 18.440(0.010) | 18.094(0.016) | 17.770(0.019) |
| 4    | 16.819(0.130) | 15.770(0.009) | 15.156(0.013) | 14.637(0.015) |
| 5    | 16.932(0.007) | 16.355(0.004) | 16.005(0.007) | 15.669(0.008) |
| 6    | 18.084(0.025) | 16.932(0.006) | 16.210(0.009) | 15.587(0.010) |
| 7    | 17.992(0.163) | 17.089(0.009) | 16.519(0.013) | 16.018(0.014) |
| 8    | 17.503(0.007) | 16.647(0.005) | 16.157(0.007) | 15.680(0.013) |
| 9    | 18.274(0.124) | 17.513(0.007) | 17.080(0.012) | 16.672(0.013) |
| 10   | 15.544(0.014) | 14.710(0.006) | 14.231(0.009) | 13.778(0.017) |
Table 2. Journal of the Observations.

| JD  | DATE     | Telescope | B  | $V_M$ | V     | R     | $R_M$ | I         |
|-----|----------|-----------|----|-------|-------|-------|--------|-----------|
| (2450000+) |          |           |    |       |       |       |        |           |
| 646.31 | 16-07-97 | 1.3m      |    | 17.364(0.011) |       |       | 16.761(0.005) |           |
| 661.28 | 31-07-97 | 1.3m      |    | 17.507(0.106) |       |       | 16.968(0.017) |           |
| 670.21 | 09-08-97 | 1.3m      |    | 17.570(0.013) |       |       | 17.034(0.017) |           |
| 670.80 | 10-08-97 | 2.3m      |    | 18.007(0.05) | 17.375(0.01) | 17.104(0.05) | 16.911(0.01) |           |
| 681.74 | 21-08-97 | 1.3m      |    | 17.663(0.029) |       |       | 17.133(0.019) |           |
| 698.79 | 07-09-97 | 2.3m      |    | 18.210(0.04) | 17.593(0.03) | 17.321(0.03) |           |           |
| 700.22 | 08-09-97 | 1.3m      |    | 17.826(0.100) |       |       | 17.288(0.021) |           |
| 709.27 | 17-09-97 | 1.3m      |    | 17.867(0.034) |       |       | 17.396(0.034) |           |
| 720.16 | 28-09-97 | 1.3m      |    | 17.963(0.029) |       |       | 17.457(0.014) |           |
| 727.05 | 05-10-97 | 1.3m      |    | 18.044(0.024) |       |       | 17.501(0.023) |           |
| 739.06 | 17-10-97 | 1.3m      |    | 18.139(0.085) |       |       | 17.574(0.036) |           |
| 760.09 | 07-11-97 | 1.3m      |    | 18.210(0.095) |       |       | 17.703(0.101) |           |
| 775.06 | 22-11-97 | 1.3m      |    | 18.363(0.020) |       |       | 17.802(0.016) |           |
| 805.66 | 23-12-97 | 2.3m      |    | 18.755(0.01) | 18.193(0.01) | 17.950(0.01) | 17.917(0.01) |           |
| 814.07 | 31-12-97 | 1.3m      |    | 18.557(0.034) |       |       | 18.172(0.029) |           |
| 825.96 | 12-01-98 | 1.3m      |    | 18.509(0.055) |       |       | 18.100(0.036) |           |
| 835.04 | 21-01-98 | 1.3m      |    | 18.661(0.037) |       |       | 18.128(0.022) |           |
| 862.97 | 18-02-98 | 1.3m      |    | 18.781(0.026) |       |       | 18.277(0.019) |           |
| 870.97 | 26-02-98 | 1.3m      |    | 18.879(0.061) |       |       | 18.355(0.039) |           |
| 888.92 | 16-03-98 | 1.3m      |    | 18.904(0.034) |       |       | 18.417(0.082) |           |
| 916.54 | 13-04-98 | 1.3m      |    | 19.260(0.063) |       |       | 19.468(0.083) |           |
| 1008.88 | 14-07-98 | 1.3m      |    | 19.630(0.067) |       |       | 19.714(0.051) |           |
| 1026.87 | 01-08-98 | 1.3m      |    | 20.119(0.064) |       |       | 19.884(0.085) |           |
| 1047.83 | 22-08-98 | 1.3m      |    | 20.362(0.135) |       |       | 19.928(0.076) |           |
| 1053.83 | 28-08-98 | 1.3m      |    | 20.458(0.136) |       |       | 20.005(0.110) |           |
| 1056.81 | 31-08-98 | 1.3m      |    | 20.472(0.101) |       |       | 20.149(0.116) |           |
| 1062.83 | 06-09-98 | 1.3m      |    | 20.458(0.233) |       |       | 20.149(0.116) |           |
| 1072.70 | 16-09-98 | 1.3m      |    | 20.495(0.130) |       |       | 20.149(0.116) |           |
| 1086.80 | 30-09-98 | 1.3m      |    | 20.532(0.214) |       |       | 20.149(0.116) |           |
| 1101.71 | 15-10-98 | 1.3m      |    | 21.246(0.269) |       |       | 20.685(0.185) |           |
| 1107.64 | 21-10-98 | 1.3m      |    | 21.356(0.092) |       |       | 20.970(0.234) |           |
| 1113.73 | 27-10-98 | 1.3m      |    | 21.425(0.195) |       |       |           |           |
Table 3. K-corrected and $L_{UV}$OIR magnitudes for SN 1997cy.

| JD (2450000+) | B (mag) | V (mag) | R (mag) | I (mag) | $L_{UV}$OIR ($\log_{10}$(ergs s$^{-1}$)) |
|---------------|---------|---------|---------|---------|-----------------------------------------|
| 646.31        | 17.27   | 16.96   |         |         | 43.32                                   |
| 661.28        | 17.41   | 17.17   |         |         | 43.25                                   |
| 670.21        | 17.48   | 17.23   |         |         | 43.23                                   |
| 670.80        | 18.04   | 17.48   | 17.25   | 16.92   |                                         |
| 681.74        | 17.57   | 17.33   |         |         | 43.19                                   |
| 698.79        | 18.28   | 17.72   | 17.48   |         |                                         |
| 700.22        | 17.73   | 17.49   |         |         | 43.12                                   |
| 709.27        | 17.77   | 17.60   |         |         | 43.10                                   |
| 720.16        | 17.87   | 17.66   |         |         | 43.06                                   |
| 727.05        | 17.95   | 17.70   |         |         | 43.04                                   |
| 739.06        | 18.04   | 17.77   |         |         | 43.01                                   |
| 760.09        | 18.12   | 17.90   |         |         | 42.97                                   |
| 775.06        | 18.27   | 18.00   |         |         | 42.91                                   |
| 805.66        | 18.95   | 18.41   | 18.18   | 18.04   |                                         |
| 814.07        | 18.46   | 18.37   |         |         | 42.80                                   |
| 825.96        | 18.47   | 18.30   |         |         | 42.81                                   |
| 835.04        | 18.57   | 18.33   |         |         | 42.79                                   |
| 862.97        | 18.69   | 18.48   |         |         | 42.74                                   |
| 870.97        | 18.78   | 18.56   |         |         | 42.70                                   |
| 888.92        | 18.81   | 18.62   |         |         | 42.68                                   |
| 916.54        | 19.17   |         |         |         |                                         |
| 1008.88       | 19.54   | 19.67   |         |         | 42.33                                   |
| 1026.87       | 20.02   | 19.91   |         |         | 42.18                                   |
| 1047.83       | 20.27   | 20.08   |         |         | 42.10                                   |
| 1053.83       | 20.36   | 20.13   |         |         | 42.07                                   |
| 1056.81       | 20.38   | 20.21   |         |         | 42.05                                   |
| 1062.83       | 20.36   |         |         |         |                                         |
| 1072.70       | 20.4    | 20.35   |         |         | 42.02                                   |
| 1086.80       | 20.44   |         |         |         |                                         |
| 1101.71       | 21.15   | 20.89   |         |         | 41.76                                   |
| 1107.64       | 21.26   | 21.17   |         |         | 41.68                                   |
| 1113.73       | 21.33   |         |         |         |                                         |
Before
