THE ASTROPHYSICAL JOURNAL, 533:320–328, 2000 April 10

SN 1997cy/GRB 970514: A NEW PIECE IN THE GAMMA-RAY BURST PUZZLE?

LISA M. GERMANY
Research School of Astronomy and Astrophysics, The Australian National University, Private Bag, Weston Creek P.O., ACT 2611, Australia; lisa@mso.anu.edu.au
DAVID J. REISS
Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580; reiss@astro.washington.edu
ELAINE M. SADLER
School of Physics, University of Sydney, NSW 2006, Australia; EMS@Physics.usyd.edu.au
BRIAN P. SCHMIDT
Research School of Astronomy and Astrophysics, The Australian National University, Private Bag, Weston Creek P.O., ACT 2611, Australia; brian@mso.anu.edu.au
AND
C. W. STUBBS
Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580; stubbs@astro.washington.edu
Received 1999 June 7; accepted 1999 December 3

ABSTRACT

We present observations of SN 1997cy, a supernova (SN) discovered as part of the Mount Stromlo Abell Cluster SN Search (Reiss et al.), which does not easily fit into the traditional classification scheme for supernovae. This object's extraordinary optical properties and coincidence with GRB 970514, a short duration gamma-ray burst (GRB), suggest a second case, after SN 1998bw/GRB 980425, for a SN-GRB association. SN 1997cy is among the most luminous SNe yet discovered ($M_R \ll -20.1$, $H_0 = 65$) and has a peculiar spectrum. We present evidence that SN 1997cy ejected approximately 2.6 $M_\odot$ of ^{56}Ni, supported by its late-time light curve and Fe II/[Fe III] 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 associated with GRB 970508 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 GRB 970514 and SN 1997cy is suggestive, it is not conclusive. However, if this association is real, follow-up of short duration GRBs detected with BATSE or *HETE2* should reveal objects similar to SN 1997cy.

Subject headings: gamma rays: bursts — supernovae: individual (SN 1997cy)

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. 1998a; Djorgovski et al. 1998) have demonstrated the enormous energies involved with these intriguing objects. However, the association of GRB 980425 with SN 1998bw (Galama et al. 1998; Kulkarni et al. 1998b) 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 that 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 GRB 980425 with a peculiar SN suggests that other such associations are likely. Evidence in support of this comes from Bloom et al. (1999), who argue that the extreme reddening in the late-time optical afterglow of GRB 980326 is due to the emergence of an underlying SN 1998bw–type light curve that overtook the afterglow about 1 week after the burst. Galama et al. (2000) and Reichart (1999) have also shown that the late-time light curve and spectral energy distribution of the afterglow of GRB 970228 is consistent with the emergence of an underlying SN 1998bw–type object.

Unfortunately, the statistics are not usually compelling for singling out individual objects because of 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 § 2, we provide evidence that GRB 980514 is associated with SN 1997cy in § 3, and in § 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, $H_0 = 65$ km s^{-1} 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 $\alpha = 4^{\rm h}32^{\rm m}54^{\rm s}.81$, $\delta = -61°42'57''.9$ (J2000) is offset from the center of its host galaxy by $0''.9$ east and $1''.4$ north. Unfortunately, the discovery image was the first of the observing season, and the most recent prediscovery 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 1.5 m 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) 2.3 m 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 1.3 m telescope, and in the $BV(RI)_{\rm KC}$ system with the MSSSO 2.3 m telescope for 15 months. Additional photometric and spectroscopic observations have been taken at European Southern Observatory and are 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 1.3 m 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 cannot apply the above techniques for extracting SN magnitudes to the $BV(RI)_{\rm KC}$ MSSSO 2.3 m telescope 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 $R_{\rm KC}$ and $I_{\rm KC}$) based on the galaxy magnitude. This magnitude is derived from the MSSSO 1.3 m V_M and R_M template images within this same $3''$ aperture and corrected to $BV(RI)_{\rm KC}$ using the V_M and R_M transformations calculated by Bessell & Germany (1999).

We put the local comparison stars onto the $BV(RI)_{\rm KC}$ standard system under photometric conditions obtained with the CTIO 1.5 m on 1999 February 18 and 1999 March 9 and the CTIO 0.9 m on 1999 February 28. We determined the transformation coefficients to the $BV(RI)_{\rm KC}$ 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 $BV(RI)_{\rm KC}$ standard system to the V_M and R_M system. These transformations are as follows:

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

$$R_M = -0.154(V - I) + R\ . \tag{2}$$

We apply equations (1) and (2) to the photometry of the local comparison stars in the $BV(RI)_{\rm KC}$ 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 1.3 m 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 $R_{\rm KC}^{(z=0)}$ are an order of magnitude larger than correcting V and $R_{\rm KC}$ 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 $R_{\rm KC}$ data, respectively. SN 1997cy is a unique event without

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)

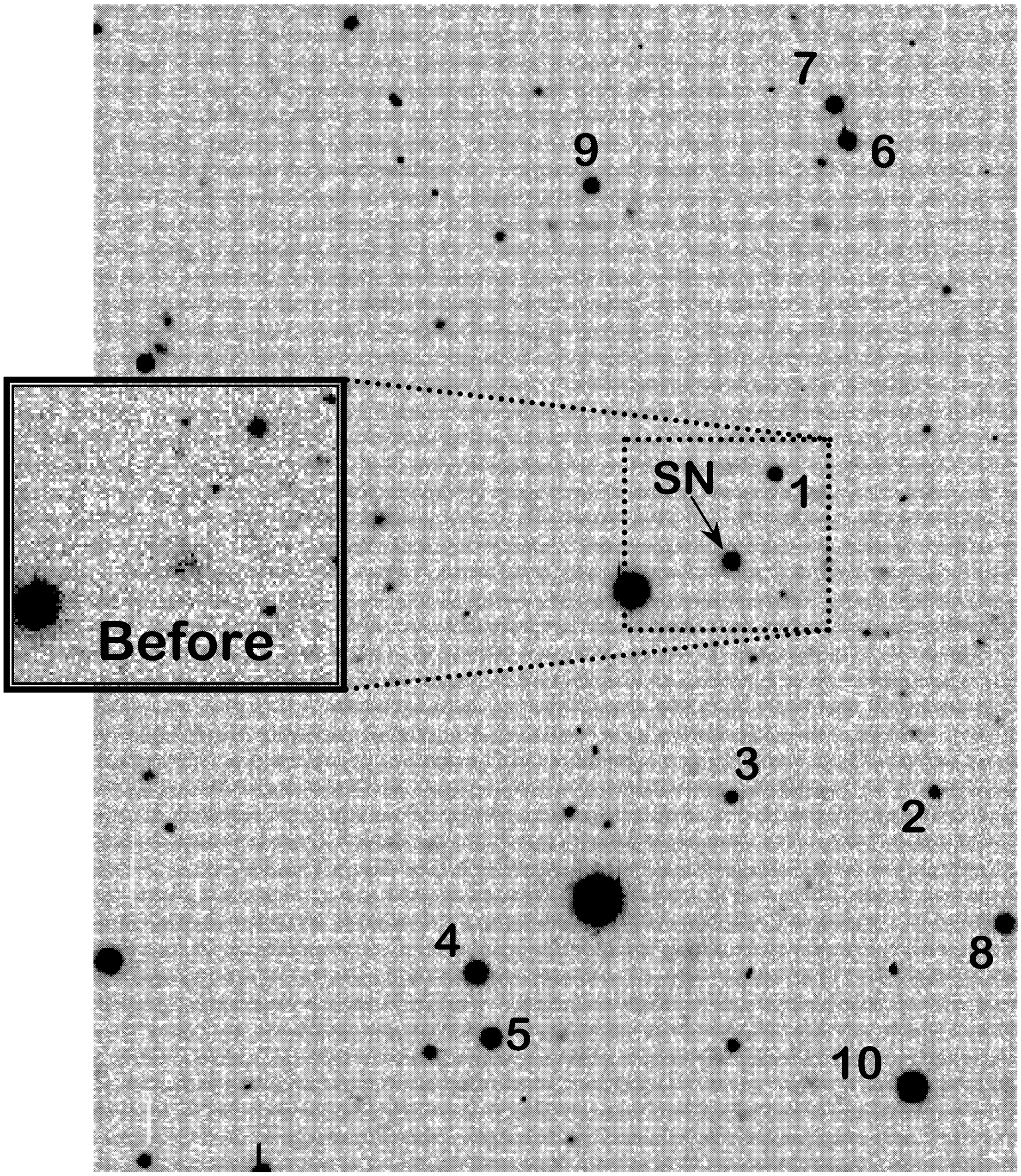

FIG. 1.—Field of SN 1997cy showing pre- and post-SN images of the galaxy and the positions of the field reference stars.

good spectrophotometry, and therefore these *k*-corrections are uncertain and estimated to be about as good as their size, ~0.15 mag. As a result of 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 1.3 m.

3. IS SN 1997cy GRB 970514?

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 prediscovery images. During this 4 month period, 119 BATSE events were detected[1], two of which overlapped SN 1997cy's position within 2 σ. These were GRB 970403 (1.92 σ, 17°.3 from SN) and GRB 970514 (0.23 σ, 0°.88 from SN). GRB 970514's proximity is clearly unexpected—it is the closest event to SN 1997cy's position yet detected by BATSE (1991 April through 1999 May) by a factor of 2.5. Using the prescription of Wang & Wheeler (1998),[2] the probability that a 0.23 σ event will occur randomly, given the 119 BATSE events and their respective error circles, is 1.7%—an unlikely occurrence. The fact that

---

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

[2] $p = 1 - \Pi_{i=1}^{N}\{1 - [\pi(0.23\sigma_i)^2/4\pi]\}$, where σ_i is the 1 σ 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.

TABLE 2

JOURNAL OF THE OBSERVATIONS.

JD (2,450,000+)	Date (dd/mm/yy)	Telescope	B	V_M	V	R	R_M	I
646.31	16/07/97	1.3 m	...	17.364(0.011)	...	...	16.761(0.005)	...
661.28	31/07/97	1.3 m	...	17.507(0.106)	...	...	16.968(0.017)	...
670.21	09/08/97	1.3 m	...	17.570(0.013)	...	...	17.034(0.017)	...
670.80	10/08/97	2.3 m	18.007(0.05)	...	17.375(0.01)	17.104(0.05)	...	16.911(0.01)
681.74	21/08/97	1.3 m	...	17.663(0.029)	...	...	17.133(0.019)	...
698.79	07/09/97	2.3 m	18.210(0.04)	...	17.593(0.03)	17.321(0.03)	...	...
700.22	08/09/97	1.3 m	...	17.828(0.100)	...	...	17.288(0.021)	...
709.27	17/09/97	1.3 m	...	17.867(0.034)	...	...	17.396(0.034)	...
720.16	28/09/97	1.3 m	...	17.963(0.029)	...	...	17.457(0.014)	...
727.05	05/10/97	1.3 m	...	18.044(0.024)	...	...	17.501(0.023)	...
739.06	17/10/97	1.3 m	...	18.139(0.085)	...	...	17.574(0.036)	...
760.09	07/11/97	1.3 m	...	18.210(0.095)	...	...	17.703(0.101)	...
775.06	22/11/97	1.3 m	...	18.363(0.020)	...	...	17.802(0.016)	...
805.66	23/12/97	2.3 m	18.755(0.01)	...	18.193(0.01)	17.950(0.01)	...	17.917(0.01)
814.07	31/12/97	1.3 m	...	18.557(0.034)	...	...	18.172(0.029)	...
825.96	12/01/98	1.3 m	...	18.569(0.055)	...	...	18.100(0.036)	...
835.04	21/01/98	1.3 m	...	18.661(0.037)	...	...	18.128(0.022)	...
862.97	18/02/98	1.3 m	...	18.781(0.026)	...	...	18.277(0.019)	...
870.97	26/02/98	1.3 m	...	18.879(0.061)	...	...	18.355(0.039)	...
888.92	16/03/98	1.3 m	...	18.904(0.034)	...	...	18.417(0.082)	...
916.54	13/04/98	1.3 m	...	19.260(0.063)	...	...	...	...
1008.88......	14/07/98	1.3 m	...	19.630(0.067)	...	...	19.468(0.083)	...
1026.87......	01/08/98	1.3 m	...	20.119(0.064)	...	...	19.714(0.051)	...
1047.83......	22/08/98	1.3 m	...	20.362(0.135)	...	...	19.884(0.085)	...
1053.83......	28/08/98	1.3 m	...	20.458(0.136)	...	...	19.928(0.076)	...
1056.81......	31/08/98	1.3 m	...	20.472(0.101)	...	...	20.005(0.110)	...
1062.83......	06/09/98	1.3 m	...	20.458(0.233)	...	...	...	...
1072.70......	16/09/98	1.3 m	...	20.495(0.130)	...	...	20.149(0.116)	...
1086.80......	30/09/98	1.3 m	...	20.532(0.214)	...	...	...	...
1101.71......	15/10/98	1.3 m	...	21.246(0.269)	...	...	20.685(0.185)	...
1107.64......	21/10/98	1.3 m	...	21.356(0.092)	...	...	20.970(0.234)	...
1113.73......	27/10/98	1.3 m	...	21.425(0.195)	...	...	...	...

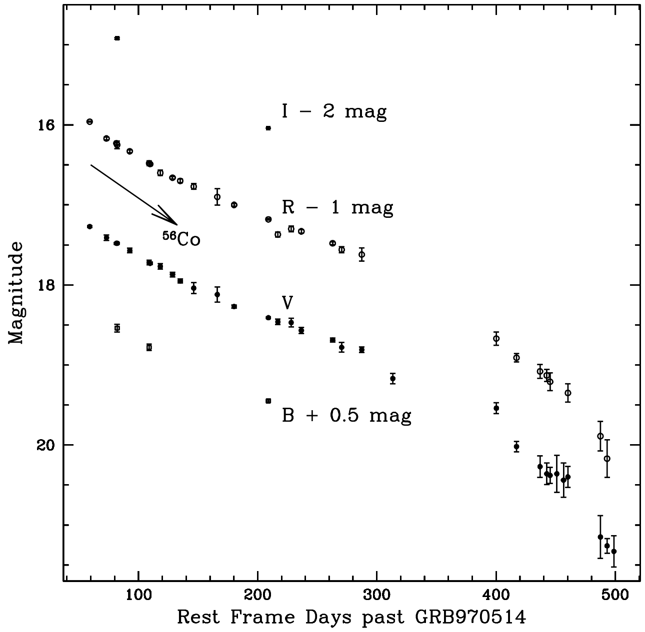

FIG. 2.—$BV(RI)_{\mathrm{KC}}$ light curves of SN 1997cy shown with the decay rate of ^{56}Co, k-corrected to $z = 0$.

two objects are found within a 2 σ radius, however, is not surprising. Over this time frame with the 119 events observed, 2 ± 1.5 random coincidences of this significance are expected.

GRB 970514 had a smaller error circle (3°.7) than a typical BATSE burst, and the 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° (0.23 σ) away from GRB 970627 (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).

TABLE 3

K-CORRECTED AND L_{UVOIR} MAGNITUDES FOR SN 1997cy.

JD (2,450,000+)	B (mag)	V (mag)	R (mag)	I (mag)	L_{UVOIR} [$\log_{10}$ (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	...	...	...

As a sanity check, we cross-correlated the entire BATSE (up through 1999) catalog with the 677 SNe discovered from 1991 to 1999[3] and looked for SNe that had a GRB burst closer than 1° within 121 days of discovery. Apart from SN 1997cy, five objects emerge, in agreement with the expected number of chance coincidences, 4.5 ± 2.5, for this data set. Of these five objects with coincidences, two are SNe 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/GRB 970514.

We have taken a conservative approach in deriving the above likelihoods of a chance coincidence between GRB 970514 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 GRB 970514 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 while making the reasonable assumption that SN 1997cy is indeed GRB 970514.

4. PROPERTIES OF GRB 970514 AND SN 1997cy

4.1. *GRB 970514*

GRB 970514 was detected on 1997 May 14, with BATSE on board the *Compton Gamma Ray Observatory*. The BATSE burst profile indicated that GRB 970514 was a member of the fast rise exponential decay subclass of single-peak events and had a duration of ~0.2 s. No current GRB model is capable of producing a burst as short as this, or any burst at all if the progenitor for SN 1997cy was a red supergiant (MacFadyen, Woosle, & Heger 1999). 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 GRB 980425. If we assume that GRB 970514 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 GRB 980425 released (Galama et al. 1998) but $\sim 10^4$ times less than other bursts with measured redshifts.

---

[3] http://athena.pd.astro.it/~supern/.

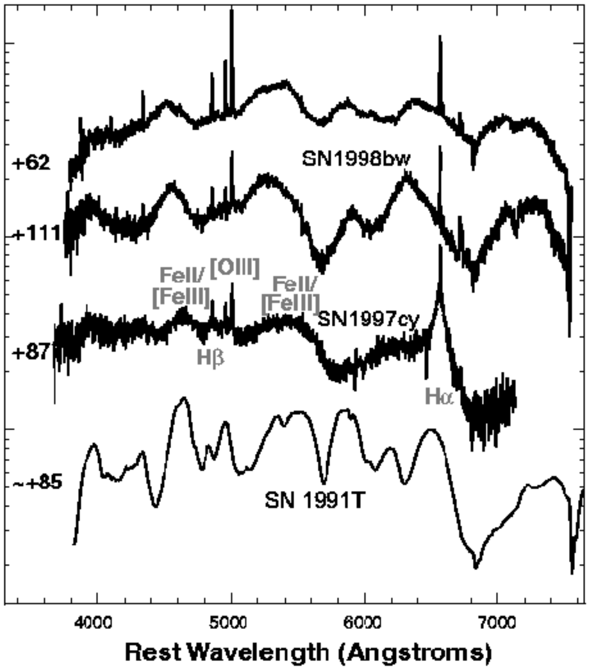

FIG. 3.—Spectra of SN 1998bw taken 62 and 111 days after GRB 980425, SN 1997cy taken 87 days after GRB 970514, and SN 1991T at 85 days after explosion. SN 1997cy is a distinctly different object but seems to have Fe II/[Fe III] features in common with SN 1991T at a similar age and a Hα profile similar to those SNe thought to be undergoing circumstellar interaction.

Emission was detected above 300 keV, marking it as a high-energy (HE) burst (Pendleton et al. 1997). These properties set GRB 970514 apart from all other GRBs that have had an identified optical transient.

Given the association of GRB 980425 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 GRB 980425. 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, GRB 970514 contains HE emission and displays a cusp rather than a rounded maximum. Unfortunately, there was no immediate radio[4] or X-ray followup of GRB 970514, 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 2.3 m telescope on 1997 August 9, 87 days after GRB 970514. Also plotted are MSSSO 2.3 m spectra of SN 1998bw that 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) owing to the absence of Si, H, and He lines that are representative of Type Ia, II, and Ib SNe, respectively. SN 1997cy appears to be a hybrid object, containing the H lines present in Type II SNe as well as Fe II/[Fe III] lines found in late-time spectra of Type Ia SNe (Branch et al. 1983). Such an object cannot be classified under the conventional SN 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 [Fe III] typical of late-time Type Ia spectra.

The origin of the broad absorption feature extending from 5645 to 6115 Å and centered 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 toward 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 GRB 970514. Hα still dominates the spectrum although it appears narrower than in the spectrum taken 87 days after GRB 970514. 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 that of SN 1997cy. It displays an intense Hα emission line, a broad absorption feature centered near 5970 Å, and broad undulations similar to SN 1997cy (Filippenko, Leonard, & Riess 1999; Jha et al. 1999;

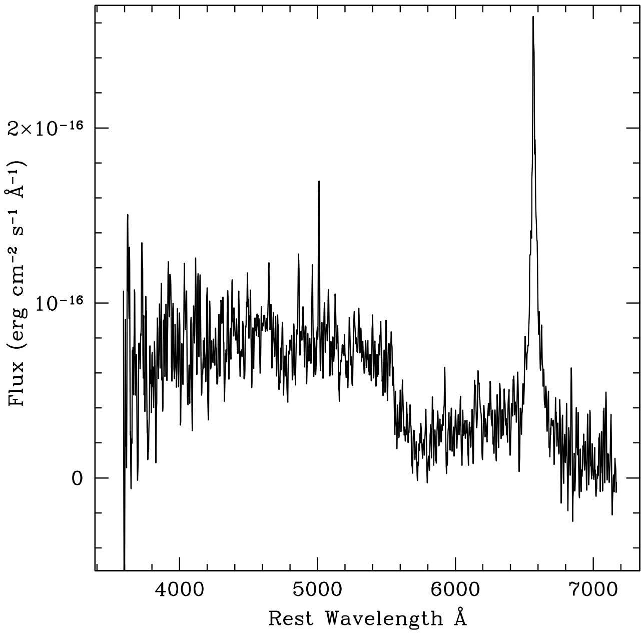

FIG. 4.—Binned spectrum of SN 1997cy taken 408 days after GRB 980514. The spectrum shows that the SN has evolved little in the year since its discovery.

---

[4] However, late-time observations with the Australia Telescope Compact Array were obtained and are discussed in § 4.4.

Cappellaro, Turatto, & Mazzali 1999). In addition, it was atypically luminous $M_V < -19.4$ ($H_0 = 65$; Jha et al. 1999) and has been linked to GRB 980910 (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 $L_{\rm UVOIR}$ light curve by integrating over the V_M, R_M, and $BV(RI)_{\rm KC}$ 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). Assuming SN 1997cy is not dominated by dust emission and in keeping with the observed properties of SNe, we extended the IR with a Rayleigh-Jeans tail and truncated the UV with a function that declined much faster than a blackbody. 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 (assuming that there are no unexpected processes related to circumstellar interaction that output significant amounts of flux in the UV) and 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 $L_{\rm UVOIR}$ 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 $L_{\rm UVOIR}$ 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. The error bar includes zero-point uncertainties and uncertainties in the flux extrapolation where we have assumed no UV or IR excesses as described above. Since most of the data was taken with the MSSSO 1.3 m telescope, the shape of the light curve should be accurate to 5% and the error bar merely acts to shift the entire curve to higher or lower $L_{\rm UVOIR}$. 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 can be most easily explained as circumstellar interaction that has subsequently decayed. This picture is consistent with the presence of Fe II/[Fe III] 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. K. Nomoto et al. (1999, private communication) have modelled SN 1997cy's light curve under this latter assumption and find they can reproduce this late-time behavior with an extremely energetic (8×10^{52} ergs) SN explosion expanding into dense circumstellar material. A clumpy circumstellar medium may allow a somewhat smaller explosion energy. Although we do not have a good handle on the physical situation of the nebula, given the age of SN 1997cy and the sudden reversion back to the ^{56}Co line at late times, it is unlikely that ionization freeze-out (Fransson & Kozma 1993) is responsible for the excursion. Regardless of the cause, the energy output is large with the integral of $L_{\rm UVOIR}$ from discovery to 450 days later yielding 1.6×10^{50} ergs.

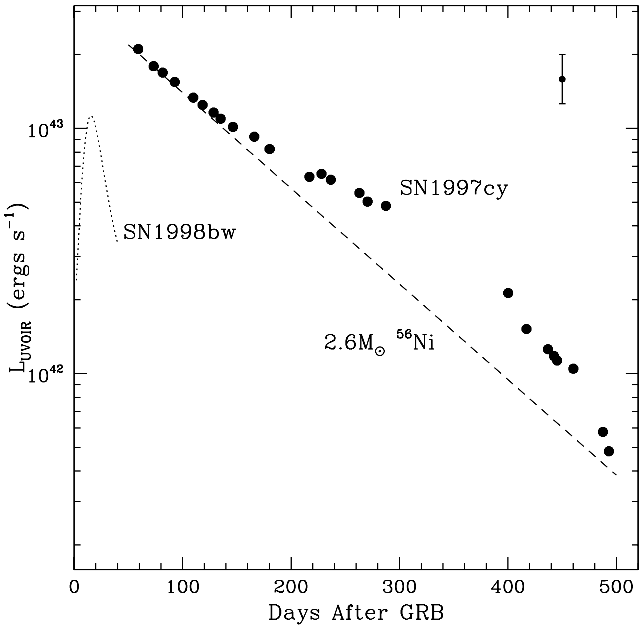

FIG. 5.—Bolometric light curve of SN 1997cy compared to that of SN 1998bw and a simple model showing the production of 2.6 $M_\odot$ of ^{56}Co. The error bar in the top corner represents a systematic error of 20%.

SN 1997cy is unlike any other SN observed (except 1999E previously discussed), and its unusual nature and coincidence with GRB 970514 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 GRB 970508 (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 GRB 970508, 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 $BV(RI)_{\rm KC}$ 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 GRBOT 970508 (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 GRBOT 970508 by about 1.3 mag. While it was earlier demonstrated that SN 1997cy is declining with a rate remarkably consistent with the 77 day half-life of ^{56}Co, a

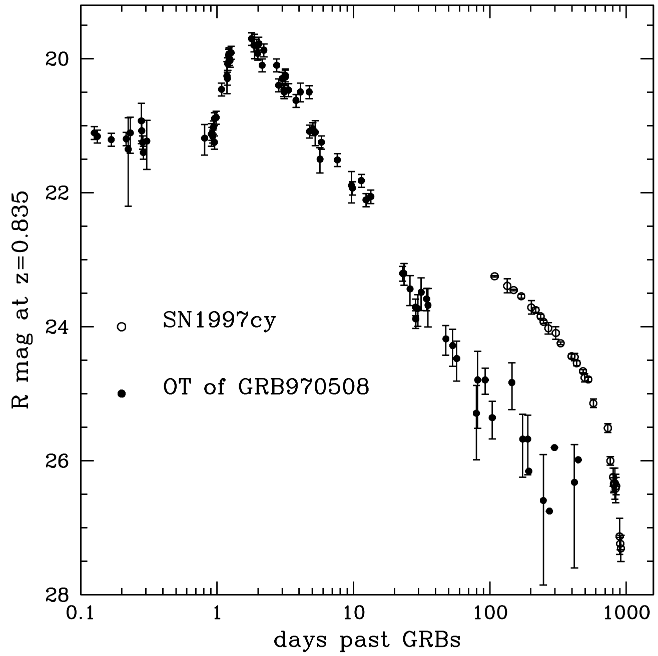

FIG. 6.—*R* light curve of the OT associated with GRB 970508 compared to the *R* light curve of SN 1997cy as it would appear at this same redshift. SN 1997cy is a factor of 3 brighter than this GRBOT 970508 and exhibits a similar light curve behavior in the areas of overlap.

similar analysis of GRBOT 970508'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 GRBOT 970508 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}Co to ^{56}Fe is responsible for their late-time energy output.

Because of the different properties between GRB 970514 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 (GRB 970508 is 5000 times more luminous than GRB 970514 given their respective redshifts of $z = 0.835$ and $z = 0.063$) is naturally explained by relativistic beaming, where distant GRBs are beamed toward us, but GRB 970514 had no preferred orientation. This model demands that the relativistic beaming factor, γ, for GRBs is low, $\gamma < 10$. Larger values of γ would make the chance of seeing any gamma rays from SN 1997cy impossibly small. This conclusion is valid, however, only if we assume that GRB 970514 belongs to the same general class of objects that make up the observed GRBOTs—a dubious assumption.

The existence of SN 1998bw/GRB 980425 complicates issues because it appears to be a very different object compared to SN 1997cy/GRB 970514 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 that lead to GRBs.

4.4. *Late-Time Radio Observations of SN* 1997*cy*

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 hr session on 1998 September 15. 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 at 20 cm and 3″.6 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 μJy beam^{-1} at 20 cm and 68 μJy beam^{-1} at 13 cm. We therefore adopt 3 σ 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 2.3×10^{21} W Hz^{-1} and 2.0×10^{21} W Hz^{-1} for the radio luminosity at 20 and 13 cm, respectively.

Unfortunately, the upper limit of 2.3×10^{21} W Hz^{-1} 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 5×10^{21} W Hz^{-1}, but only exceeded 2.3×10^{21} W Hz^{-1} for a period of about 40 days between 40 and 80 days after explosion (Kulkarni et al. 1998b). 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 1.8×10^{21} W Hz^{-1} almost 5 yr 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 5 yr). Another deep radio observation in 2–3 yr 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 [$M_R = -20.1$ ($H_0 = 65$) 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 prodigous output of ^{56}Ni with our simple model indicating that it put out 30 times more ^{56}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 (Paczyński 1997; Iwamoto et al. 1998), collapsar (Woosley 1993, 1996), or possibly a pair production supernova (Woosley 1986), with the latter being the only model that can easily output as much as 2.6 $M_\odot$ of ^{56}Ni.

The levelling off of the light curve at late times and later reversion to the ^{56}Co decay line is probably due to energy input from circumstellar interaction that started to diminish in its effect at approximately 300 days after explosion. This conclusion is supported by the presence of a narrow and broad component to the Hα and the absence of Hα absorption (Chugai 1991). The material illuminated by this circumstellar interaction may pose problems for the clean environment necessary for some gamma-ray 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 GRB 970514 is suggestive but not conclusive. However, other SN/GRB events like SN 1998bw and SN 1999E and the existence of SN 1998bw–type light curves in GRB afterglows (Bloom et al. 1999; Galama et al. 2000; Reichart 1999) have strengthened the SN/GRB case. If these associations are real, there are now several GRBs with measured redshifts below $z < 0.1$ and many more at $z > 0.5$ (Djorgovski et al. 1998). Despite the obvious problems associated with such small numbers and the nonuniform 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 that give rise to GRBs. The very different properties of both the SNe and GRBs in the SN 1997cy/GRB 970514 and SN 1998bw/GRB 980425 associations indicate that SN 1997cy is a distinct object from SN 1998bw and that we are already seeing two different progenitors for GRBs.

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 1.3 m 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/GRB 970514 and SN 1998bw/GRB 980425 are real, or pure chance. Only with more data can we learn how SNe fit into the big picture of GRBs.

The authors would like to thank Sebastian Juraszek and Vince McIntyre for carrying out the ATCA observations, and Ron Ekers and Mark Wieringa for allowing us to use their unpublished data. We gratefully acknowledge helpful discussions with Marc Kippen on the BATSE data, Stan Woosley, Ron Eastman, Peter Garnavich, and Kenichi Nomoto on the light curves and spectra of SN 1997cy, Geoff Bicknell on the formation of gamma rays, and David Branch on Fe II lines in SNe Ia. We would also like to thank Professor Jeremy Mould for his generous allocation of Director's Discretionary time for the Mount Stromlo Abell Cluster Supernova Search on the MSSSO 1.3 m telescope. D. Reiss and C. Stubbs gratefully acknowledge the support of the Packard Foundation and the National Science Foundation.

REFERENCES

Abell, C. O., Corwin, H. G., & Olowin, R. P. 1989, ApJS, 70, 1

Benetti, S., Pizzella, A., & Wheatley, P. J. 1997, IAU Circ. 6708

Bessell, M. S. 1990, PASP, 102, 1181

———. 1999, PASP, submitted

Bessell, M. S., & Germany, L. M. 1999, PASP, 111, 1421

Bloom, J. S., et al. 1999, Nature, 401, 453

Bloom, J. S., Kulkarni, S. R., Harrison, F., Prince, T., & Phinney, E. S. 1998, ApJ, 507, L25

Bond, H. E. 1997, IAU Circ. 6654

Branch, D., Lacy, C. H., McCall, M. L., Uomoto, A., Wheeler, J. C., Wills, B. J., & Sutherland, P. G. 1983, ApJ, 270, 123

Cappellaro, E., Turatto, M., & Mazzali, P. 1999, IAU Circ. 7091

Chugai, N. N. 1991, MNRAS, 250, 513

Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Goodrich, R., Frail, D. A., Piro, L., & Palazzi, E. 1998, ApJ, 508, L17

Dreiling, L. A. & Bell, R. A. 1980, ApJ, 241, 736

Filippenko, A. V., Leonard, D. C., & Riess, A. G. 1999, IAU Circ. 7091

Fransson, C., & Kozma, C. 1993, ApJ, 408, L25

Fruchter, A. S., et al. 1999, ApJ, submitted (astro-ph/9903236)

Galama, T. J., et al. 1998, Nature, 395, 670

———. 2000, ApJ, in press

Germany, L. M., Reiss, D. J., Schmidt, B. P., & Stubbs, C. W. 1997, IAU Circ. 6706

Iwamoto, K., et al. 1998, Nature, 395, 672

Jha, S., Garnavich, P., Challis, P., & Kirshner, R. P. 1999, IAU Circ. 7090

Kippen, R. M., et al. 1998, ApJ, 506, L27

Kulkarni, S., et al. 1998a, Nature, 393, 35

———. 1998b, Nature, 395, 663

Landolt, A. U. 1992, AJ, 102, 208

MacFadyen, A. I., Woosley, S. E., & Heger, A. 1999, preprint (astro-ph/9910034)

Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., Steidel, C. C., Adelberger, K. L., Frail, D. A., Costa, E., & Frontera, F. 1997, Nature, 387, 879

Norris, J. P., Bonnell, J. T., & Watanabe, K. 1998, ApJ, 518, 901

Paczyński, B. 1997, ApJ, 484, L45

Patat, F., & Piemonte, A. 1998 IAU Circ. 6918

Pendleton, G. N., et al. 1997, ApJ, 489, 175

Phillips, M. M., Wells, L. A., Suntzeff, N. B., Hamuy, M., Leibundgut, B., Kirshner, R. P., & Foltz, C. B. 1992, AJ, 103, 1632

Reichart, D. E. 1999, ApJ, 521, L111

Reiss, D. J., Germany, L. M., Schmidt, B. P., & Stubbs, C. W. 1998, AJ, 115, 26

Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342

Schmidt, B. P., et al. 1998, ApJ, 507, 46

Stathakis, R. A., & Sadler, E. M. 1993, MNRAS, 250, 786

Stetson, P. B. 1987, PASP, 99, 191

Stubbs, C. W., et al. 1993, Proc. SPIE, 1900, 192

Teague, P. F., Carter, D., & Gray, P. M. 1990, ApJS, 72, 715

Thorsett, S. E., & Hogg, D. W. 1999, GCN Circ. 197

Tinney, C., Stathakis, R. J., Boyle, B. J., & Ekers, R. D. 1998, IAU Circ. 6901

Turatto, M., et al. 1999, preprint (astro-ph/9910324)

Turatto, M., Cappellaro, E., Danziger, I. J., Benetti, S., Gouiffes, C., & Della Valle, M. 1993, MNRAS, 262, 128

van Dyk, S. D., Weiler, K. W., Sramek, R. A., & Panagia, N. 1993, ApJ, 419, 69

van Paradijs, J., et al. 1997, Nature, 386, 686

Wang, L., & Wheeler, J. C. 1998, ApJ, 504, L87

Woosley, S. E. 1986, in Nucleosynthesis and Chemical Evolution: 16th Advanced Course of the Swiss Society of Astronomy and Astrophysics, ed. A. Audouze, C. Chiosi, & S. E. Woosley (Sauverny-Versoix, Switzerland: Geneva Obs), 133

———. 1993, ApJ, 405, 273

———. 1996, in AIP Conf. Proc. 384, Gamma-Ray Bursts: 3rd Huntsville Symposium, ed. C. Kouveliotous, M. Briggs, & G. Fishman (New York: AIP), 709

Woosley, S. E., Eastman, R. G., & Schmidt, B. P. 1998, ApJ, 516, 788