THE PROPERTIES OF SUPERNOVA 1997cy ASSOCIATED WITH GRB 970514

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ABSTRACT

The extraordinary SN 1997cy associated with GRB 970514 has been observed photometrically and spectroscopically for nearly 2 yr. At the time of discovery, SN 1997cy was the brightest supernova (SN) ever observed ($M_V < -20.1$, $v_{lin} = 19,140$ km s$^{-1}$, $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$). Up to the last available observations (600 days after the gamma-ray burst), the total time-integrated flux was equal to or larger than that expected from the complete thermalization of the $\gamma$-rays produced by $2.3 M_\odot$ of $^{56}$Co. However, starting already on day 60 the luminosity decline is slower than the $^{56}$Co decay rate, indicating that the SN ejecta was interacting with circumstellar material (CSM). The interaction appeared to weaken around day 550. The spectra of SN 1997cy are dominated at all epochs by H$\alpha$ emission, which shows at least three components of different widths, as in SN 1988Z. Several other lines with different widths are also visible, especially at early epochs. The entire light curve of SN 1997cy is reproduced by a model of the interaction of the very energetic ($E = 3 \times 10^{52}$ ergs) ejecta of a massive star ($25 M_\odot$) with the CSM, with some contribution from radioactive decays. The CSM could have been ejected with a mass-loss rate of $M \approx 4 \times 10^{-4} M_\odot$ yr$^{-1}$ as the progenitor star evolved from a blue to a red supergiant about 10$^4$ yr before the explosion. The lack of oxygen and magnesium lines in the spectra at nebular phases poses a problem for models requiring high-mass progenitors. The possibility that most of the core material of the progenitor has fallen onto a massive black hole so that the reverse shock dies at the inner edge of the H/He envelope is discussed.

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

1. INTRODUCTION

The spatial and temporal coincidence between GRB 980425 and SN 1998bw (Galama et al. 1998; Iwamoto et al. 1998) raised the issue of the association of (some) gamma-ray bursts (GRBs) with supernova (SN) explosions. So far, the study of the statistical correlation of SNe with BATSE and BATSE/Ulysses bursts has given contradictory results. Some authors have proposed that all GRBs originate from Type Ib/c SNe. These are core-collapse SNe whose progenitors have lost most or all of the hydrogen envelope (Wang & Wheeler 1998). However, only a weak correlation was found between the general list of SNe and GRBs (Kippen et al. 1998). As an alternative, it has been suggested that only a small fraction of the GRBs originate from asymmetric explosions of rare, highly energetic Type Ib/c SNe (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999). In particular, Bloom et al. (1998), on the basis of a model for the radio emission of SN 1998bw, have derived the characteristics that an SN must have in order to produce a detectable GRB (weak single burst). Again they indicate highly energetic Ib/c events as best candidate sources of (some) GRBs.

Germany et al. (1999) proposed GRB 970514 as another compelling association between a highly energetic SN and a GRB. SN 1997cy was discovered on 1997 July 16 (Germany et al. 1997) in the compact and faint galaxy number 342 of the cluster Sersic 40/6 (= Abell 3266; $z = 0.059$; $\sigma = 1211$ km s$^{-1}$; Green, Godwin, & Peach 1990). The relatively narrow H$\alpha$ emission led to the classification of SN 1997cy as a Type II SN. The epoch of the SN explosion is constrained by a prediscovery limit on March 12 and is consistent, within the uncertainties, with the association with GRB 970514, whose 3$\sigma$ error box was centered only 0$''$.88 away.

The probability of a chance association of the SN with one of the 119 BATSE events that occurred in the period between the prediscovery observation and the discovery images is 0.7% (Germany et al. 1999). After SN 1998bw, this is the most compelling case for SN/GRB association. GRB 970514 was a single-peak burst also detected above 300 keV. At the distance of SN 1997cy, the burst energy would be $\sim 4 \times 10^{48}$ ergs, which makes GRB 970514 more energetic than GRB 980425 but orders of magnitude weaker than other bursts with measured redshifts (Germany et al. 1999).

In this Letter, we present and discuss optical observations of SN 1997cy obtained up to 2.5 yr after discovery, together with a model of the light curve derived with a high progenitor mass and explosion energy.

2. LIGHT CURVE

Imaging photometry of SN 1997cy has been obtained in $BVRI$ with several telescopes at ESO–La Silla. Typical seeing was 1$''$.2. A sequence of local reference stars has been measured on seven photometric nights in order to calibrate nonphotometric data. Very deep VLT/FORS1 imaging (seeing 0$''$.6) in $V$ and $R$ about 2.5 yr after discovery did not detect the SN. Although there is very good agreement for the stars in common with Germany et al. (1999), we note a difference between our SN magnitudes and their estimates. This is small (0.15 mag) at maximum, but it increases with epoch up to 0.4 mag. We
verified that measuring the SN magnitude with different techniques, point-spread function fitting or subtraction of prediscovery images (kindly provided by B. Schmidt 1999, private communication)—the method used by Germany et al.—produces similar results even at late epochs. Artificial star experiments show that at all epochs for which we could make the comparison between the data sets, our typical errors are smaller than 0.1 mag. We believe that the inconsistency is partially due to the different passbands (Germany et al. 1999), although the modest spectral evolution of SN 1997cy should not cause a temporal dependence, and/or to incorrect flux calibration of low signal-to-noise ratio data. In particular, there is the possibility of contamination by two nearby (2°) bright knots (southeast and southwest) inside the parent galaxy, which could be severe for imaging at small scales or with bad seeing.

The light curve of SN 1997cy does not conform to the classical templates of Type II SNe, namely plateau and linear, but resembles the slow evolution of the Type IIn SN 1988Z (Turatto et al. 1993). Assuming $A_V = 0.00$ for the galactic extinction (Burstein & Heiles 1982), we get for SN 1997cy an absolute magnitude at maximum of $M_V \lesssim -20.1$. This makes SN 1997cy the brightest Type II SN discovered so far, brighter than the very luminous SN 1997C and SN 1983K ($M_V = -19.9$ and $-19.3$; Patat et al. 1994; with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$). Note that Schlegel, Finkbeiner, & Davis (1998) give $A_V = 0.07$. As far as we know, no detections at other wavelengths have been reported, except for some radio limits at 20 cm that are not very stringent (Germany et al. 1999).

The uvoir bolometric light curve of SN 1997cy obtained using the available BVRI photometry and the spectrophotometry is shown in Figure 1. Integrating the bolometric light curve, we estimate that the SN has emitted about $2 \times 10^{50}$ ergs from the day of discovery to our last detection, not including the GRB luminosity. We stress that the uvoir determinations are by necessity lower limits of the true bolometric luminosities.

### 3. RADIOACTIVE DECAY VERSUS INTERACTION

The late-time light curve of most SNe is powered by the radioactive decay of $^{56}$Co to $^{56}$Fe. If the hard $\gamma$-rays from the decay are completely thermalized in the ejecta, the mass of

!, the parent isotope of $^{56}$Co, can be estimated directly from the luminosity on the tail of the light curve. Typical $^{56}$Ni masses for Type II SNe are $\sim 0.08 M_\odot$ (e.g., SN 1987A), but extreme cases range from 0.002 to 0.02 $M_\odot$ for SN 1997D (Turatto et al. 1998) to 0.3 $M_\odot$ for SN 1992am (Schmidt 2000).

Between 60 and 120 days after the outburst, which is taken to be coincident with the GRB, the light curve of SN 1997cy matches the decline rate expected if the energy input was the decay of $^{56}$Co. The estimated initial mass of $^{56}$Ni is $2.3 M_\odot$. At 4 months the SN decline becomes slower, which suggests that another source of energy is present. Between days 250 and 550 the light curve again matches the $^{56}$Co decay of $6 M_\odot$, which is clearly dubious. Then the light curve suddenly drops, as does the H$\alpha$ emission. On day 655 the SN could not be detected with the ESO 3.6 m telescope. The last points of our bolometric light curve lie above the radioactive tail of 2.3 $M_\odot$ of $^{56}$Ni, but are compatible with a value close to that proposed by Germany et al. (1999) if we allow for some interaction. However, our observations indicate that the late drop mentioned above occurs about 100 days later than estimated by Germany et al.

Other observable signatures of the interaction, besides the slow decline, are complex line profiles evolving with time, easily detectable in the prominent H$\alpha$ line, and powerful radio and X-ray emission (Aretzaga et al. 1999). H$\alpha$ in SN 1997cy shows an unresolved emission and at least two broader components, which become narrower with time. At the epoch of the first observation, the broadest component has FWHM = 12,800 km s$^{-1}$, and its flux dominates over the intermediate (FWHM = 4300 km s$^{-1}$) component. One year after the explosion, the broadest component has almost disappeared and the intermediate component (now with FWHM = 2000 km s$^{-1}$) is the most evident spectral feature in the spectrum. SN 1997cy was last detected on 1999 April 12, when only a faint H$\alpha$ emission was detected at the 3 $\sigma$ level ($F_\lambda = 2 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$; FWHM = 1000 km s$^{-1}$).

In Figure 2 we show representative spectra of SN 1997cy at various epochs, and in Figure 3 we compare the spectra of SN 1997cy and SN 1988Z, since a certain spectral similarity between the two SNe is possibly suggestive. Lines of different widths are present in the spectra of SN 1997cy. At early epochs there are very broad bands (FWHM $\sim 300$ A)—probably blends of several lines, the strongest of which are measured at 4150, 4900, 5800, 7800, and 9100 A (Ca II IR triplet). Narrow

![Fig. 1.—The uvoir (0.32–1 $\mu$m) bolometric light curve of SN 1997cy (using the luminosity distance, $A_V = 0$ and $M_{GRB} = 4.72$). Squares come from the BVRI photometry and triangles from the spectrophotometry. The dashed lines indicate the $^{56}$Co decline slope. The rest-frame epoch is computed from GRB 970514. Also shown are the bolometric light curves of SN 1987A, SN 1988Z (Type IIn), SN 1992A (Type Ia), and SN 1998bw (Type Ic peculiar), associated to GRB 980425. Typical errors are 0.15 dex.](image1)

![Fig. 2.—Three spectra describing the evolution of SN 1997cy. The ordinate axis refers to the first spectrum (top). Other spectra have been shifted downward by $3 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ A$^{-1}$ and the last multiplied by a factor 3.](image2)

![Fig. 3.—SN 1997cy. The ordinate axis refers to the first spectrum (top). Other spectra have been shifted downward by $3 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ A$^{-1}$ and the last multiplied by a factor 3.](image3)
lines include Hα, Hβ, and [O iii] λ5007. Intermediate-width lines (FWHM ~ 2500–4300 km s⁻¹) include He i λ5876, which appears in emission between day 100 and 150 (see Fig. 3).

A multiwavelength study of SN 1988Z showed that the energy radiated from radio to X-rays was as high as 10⁵² ergs (Aretxaga et al. 1999), suggesting complete reprocessing of the mechanical energy of the ejecta in only a few years. The behavior of the interaction between the SN ejecta and a dense circumstellar medium in SN 1988Z has been modeled by Terlevich et al. (1992) in the framework of the compact supernova remnant scenario, and by Chugai & Danziger (1994), who invoked the presence of a rarefied wind together with a denser component in the form of clumps or an equatorial wind. The optical light curve, the X-ray emission, the Hα emission, and the line width evolution of SN 1988Z are generally reproduced by these models, but the resulting ejecta and circumstellar material (CSM) masses are model dependent. In what follows, both the similarities and differences between SN 1988Z and SN 1997cy should be kept in mind. The two SNe are similar in apparently having a three-component profile of the dominant Hα emission line, and their light curves, although not equally well sampled, have the same slow decline for the first 2 yr. SN 1988Z was an order of magnitude less luminous than SN 1997cy, while the complex of line blending in the 4000–6000 Å region is clearly different, as shown by careful inspection of Figure 3.

4. MODELING THE LIGHT CURVE

The similarities between SN 1997cy and SN 1988Z suggest that we investigate an interaction model for SN 1997cy as well. Our exploratory model considers the explosion of a massive star of M = 25 M☉ with a parameterized explosion energy E. We assume that the collision starts near the stellar radius at a distance rι, where the density of the CSM is ρι, and adopt for the CSM a power-law density profile ρ ∝ r⁻ⁿ. The parameters E, ρι, and n are constrained from comparison with the observations. The numerical code and input physics are the same as developed by Suzuki & Nomoto (1995).

As in the compact supernova remnant model, the regions excited by the forward and reverse shock emit mostly X-rays. The density in the shocked ejecta is so high that the reverse shock is radiative and a dense cooling shell is formed (e.g., Suzuki & Nomoto 1995; Terlevich et al. 1992). The X-rays are absorbed by the outer layers and core of the ejecta and reemitted as UV-optical photons. Narrow lines are emitted from the slowly expanding unshocked CSM photoionized by the SN UV outburst or by the radiation from the shocks, intermediate-width lines come from the shock-heated CSM, and broad lines come from either the cooler region at the interface between ejecta and CSM or the unshocked ejecta heated by inward-propagating X-rays.

Figure 4 shows the model light curve that best fits the observations. The model parameters are E = 3 × 10⁵² ergs, ρι = 2.5 × 10⁻¹⁴ g cm⁻³ at rι = 3 × 10¹⁴ cm (which corresponds to a mass-loss rate of M = 4 × 10⁻³ M☉ yr⁻¹ for a wind velocity of 10 km s⁻¹), and n = −1.6. Shown are the total luminosity from the shocked ejecta Ltot (dotted curve), the UV-optical luminosity LUV (solid curve), and the luminosity of the X-rays escaping from the ejecta Lx (dashed curve), where Lx = Ltot − LUV.

The large CSM mass and density and the very large explosion energy are necessary to have large shocked masses and thus to reproduce the observed high luminosity. In models with low E and high ρι, the reverse shock speed is too low to produce a sufficiently high luminosity. For example, a model with E = 10⁵¹ ergs and ρι as above yields a value of Ltot lower than the observed one by a factor of ~5. For high E or low ρι, the SN ejecta expand too fast for the cooling shell to absorb enough X-rays to sustain the luminosity. Therefore, E and M are constrained within a factor of ~3 of the reported values.

The slope of the light curve constrains the circumstellar density structure. If n = −2 (the case of a steady wind) is used, Ltot decreases too rapidly around day 200. The observed light curve shows a first, slight drop after day ~300. This can be reproduced if the CSM density is assumed to drop abruptly at
the radius reached by the forward shock at day 300, so that the collision becomes weaker afterwards. This change of the CSM density marks the transition of the progenitor from BSG to RSG, which should have occurred \( \sim 10^3 \) yr before the SN explosion. This is consistent with the simultaneous decrease of the H\( \alpha \) luminosity mentioned in § 3.

After this date, the light curve is powered only by the reverse shock propagating into the ejecta. After day \( \sim 550 \) the observed light curve shows a second, sharper drop, which is reproduced (Fig. 4) assuming that after the reverse shock has propagated through \( \sim 5 M_\odot \) of ejecta it encounters a region of very low density and thus dies. In other words, the model assumes that most of the progenitor’s core material fell into a massive (\( \sim 10 M_\odot \)) black hole, while only the extended H/He envelope of \( \sim 5 M_\odot \) was ejected. Therefore, both forward and reverse shocks propagated inside H/He-dominated ejecta.

However, the fact that the ejecta-CSM model with high explosion energy reproduces the light curve does not necessarily mean that the radioactive energy input is small because of the uncertainty in the model fitting. To constrain the contribution from the radioactive decay, we calculated the optical light curve of the SN caused by the combination of shock heating and radioactive decay. We find that a contribution of up to 0.7 \( M_\odot \) of \( ^{56}\text{Ni} \) is allowed. However, the decline rate of the radioactive component after day 60 is much faster than the half-life of the \( ^{56}\text{Co} \) decay because the explosion is so energetic that only a fraction of \( \gamma \)-rays is trapped in the ejecta. This implies that radioactive decay cannot explain the slope of the observed light curve even between 60 and 120 days.

### 5. DISCUSSION

The spectra of SN 1997cy obtained within about 100 days from the GRB show broad emission lines which disappear at later times, leaving only a blue continuum. Broad emission lines originate in the fast-expanding ejecta which, in the interaction model, absorb X-rays produced in the shocks. This is in principle not very different from the mechanism active in the case of radioactive powering, i.e., the deposition of hard radiation (\( \gamma \)-rays in that case). The width of the broad lines (13,000 km s\(^{-1}\)) is consistent with the outer velocity of the expanding ejecta in the interaction model (\( \sim 15,000 \) km s\(^{-1}\)).

Broad Ca \( \Pi \) emission lines are easily identified. However, the Fe \( \Pi \) and Fe \( \Pi \) emission lines that are strong in the nebular spectra of Type Ia SNe are not obviously identified. This could mean that either the ejected \( ^{56}\text{Fe} \) (i.e., \( ^{56}\text{Ni} \)) mass is small or that the densities are so high that forbidden lines are collisionally quenched. In fact, the broad feature near 4500 Å might be attributed to the Fe \( \Pi \) multiplets 37 and 38, while the very broad feature near 5000 Å may be dominated by a blend of the Fe \( \Pi \) multiplets 42, 48, and 49.

High densities in the ejecta of SN 1997cy appear, on the other hand, to be an almost inevitable conclusion: with a characteristic velocity not much higher than that of Type Ia SNe nebulae, the interaction model for SN 1997cy predicts an ejecta mass of \( \sim 5 M_\odot \) i.e., a factor of \( \sim 4 \) larger. The epoch of the SN 1997cy spectra is also much earlier than it is for Type Ia SNe in their nebular epoch (100 vs. 300 days), thus adding another factor of \( \sim 3 \) to the density. Thus, we can expect the typical density in the SN 1997cy ejecta to be \( \sim 100 \) times that of Type Ia SNe at 300 days. This implies densities of about \( 10^3 \) cm\(^{-3}\). Electron densities of course depend also on the degree of ionization, but values of at least \( 10^3 \) cm\(^{-3}\) can be expected.

If the forbidden lines are quenched, emission could occur in permitted Fe \( \Pi \) lines which may be present in the spectrum of SN 1997cy, as suggested above. Nevertheless, the excitation of Fe \( \Pi \) lines in SNe and active galactic nuclei involves processes not yet fully understood. The H\( \alpha \) profile of SN 1988Z was explained within the ejecta-CSM interaction scenario by Chugai & Danziger (1994), who derived a mass for the ejecta smaller than \( 1 M_\odot \), with a progenitor main-sequence mass of 8–10 \( M_\odot \). Modeling the light curve of SN 1988Z as the result of interaction may therefore be worthwhile, and it might indicate a larger mass for SN 1988Z. However, another property SN 1997cy and SN 1988Z have in common is that neither [O \( \Pi \)] \( \lambda 6300 \) nor Mg \( \Pi \) \( \lambda 4571 \) have been detected at any stage in their spectra. The critical densities of these lines are expected to be a few times \( 10^4 \) and a few times \( 10^5 \), respectively. The envelope density at late phases would not be expected to exceed these values. Since only stars with masses less than 8–10 \( M_\odot \) (Nomoto 1984) are expected to synthesize little oxygen, one is left with the conundrum of the missing oxygen and magnesium if it is assumed that these SNe originated from significantly higher mass stars.

The model described in the previous section might resolve this conundrum: O and Mg synthesized in the core have fallen into the black hole; the ejecta are basically the H/He layers and thus contain the original (solar abundance) heavy elements plus some heavy elements mixed from the core before fall back. If the SN formed a black hole, the progenitor mass was probably larger than \( \sim 25 M_\odot \) (e.g., Ergma & van den Heuvel 1998).

The large energy implied from the modeling of SN 1997cy and indeed its high luminosity alone might suggest a causal connection between energetic SN events (hypernovae) and the occurrence of GRBs. It appears that hypernovae occur in a variety of SN types. Objects such as SN 1998bw and SN 1997ef (Iwamoto et al. 2000) are of Type Ic, while SN 1997cy is of Type IIn. The recent SN 1999E (Cappellaro, Turrato, & Mazzali 1999), whose spectrum is identical to that of SN 1997cy, may be another Type IIn hypernova. Objects such as SN 1998Z also deserve renewed study for the reasons discussed in this Letter.

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