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MODELS FOR THE TYPE Ic HYPERNOVA SN 2003lw ASSOCIATED WITH GRB 031203

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ABSTRACT

The gamma-ray burst GRB 031203 at a redshift $z = 0.1055$ revealed a highly reddened Type Ic supernova, SN 2003lw, in its afterglow light. This is the third well-established case of a link between a long-duration GRB and a Type Ic SN. The SN light curve is obtained by subtracting the galaxy contribution and is modeled together with two spectra at near-maximum epochs. A red VLT grism 150I spectrum of the SN near peak is used to extend the spectral coverage, and in particular to constrain the uncertain reddening, the most likely value for which is $E_{G+H}(B-V) \simeq 1.07 \pm 0.05$. Accounting for reddening, SN 2003lw is ~0.3 mag brighter than the prototypical GRB-SN 1998bw. Light curve models yield a ^{56}Ni mass of $\sim 0.55\ M_{\odot}$. The optimal explosion model is somewhat more massive ($M_{\rm ej} \sim 13\ M_{\odot}$) and more energetic ($E \sim 6 \times 10^{52}$ ergs) than the model for SN 1998bw, implying a massive progenitor (40–50 $M_{\odot}$). The mass at high velocity is not very large (1.4 $M_{\odot}$ above 30,000 km s^{-1}, but only 0.1 $M_{\odot}$ above 60,000 km s^{-1}), but it is sufficient to cause the observed broad lines. The similarity of SNe 2003lw and 1998bw and the weakness of their related GRBs, GRB 031203 and GRB 980425, suggest that both GRBs may be normal events viewed slightly off-axis or a weaker but possibly more frequent type of GRB.

Subject headings: gamma rays: bursts — nuclear reactions, nucleosynthesis, abundances — supernovae: general — supernovae: individual (SN 2003lw)

1. INTRODUCTION

The first indication of a connection between long-duration gamma-ray bursts (GRBs) and Type Ic supernovae (SNe Ic) was the discovery of a bright SN Ic, SN 1998bw, in spatial and temporal coincidence with the nearby GRB 980425 ($z = 0.0085$; Galama et al. 1998). The spectra of SN 1998bw showed broad P Cygni lines of elements such as Fe, Ca, and Si, indicating expansion velocities of $\sim 0.1c$. Models of the spectra and the light curve (LC) yielded an isotropic equivalent expansion kinetic energy $E \sim 5 \times 10^{52}$ ergs (Iwamoto et al. 1998) and an ejected mass $M_{\rm ej} \sim 11\ M_{\odot}$, suggesting that SN 1998bw was the highly energetic explosion of a massive stellar core. The explosion synthesized a large mass of ^{56}Ni for a core-collapse event ($\sim 0.5\ M_{\odot}$). The progenitor of SN 1998bw was probably a very massive star ($M_{\rm ZAMS} \sim 40\ M_{\odot}$), and the remnant very likely a black hole. SNe with broad spectral features, indicative of a large E, have been called "hypernovae" (HNe).

Nebular-phase spectra of SN 1998bw were dominated by a strong [O i] 6300, 6363 Å emission, as is typical of SNe Ic, but they also showed strong lines of [Fe ii], reflecting the high ^{56}Ni production. Another peculiarity was that the [O i] line was narrower than the [Fe ii] lines. This is not expected in the spherically symmetric explosion of a CO core (Mazzali et al. 2001) and was interpreted as the result of the ejection of most ^{56}Ni along a preferential (polar) direction in an aspherical explosion (Maeda et al. 2002), reminiscent of the collapsar model for GRBs (MacFadyen & Woosley 1999). Doubts were raised about the association of SN 1998bw and GRB 980425 because of the unusual weakness of the GRB and the apparent presence of an X-ray transient inconsistent in position with the SN (Pian et al. 2000), but the reality of this transient was disproved by observations with both *XMM-Newton* (Pian et al. 2004) and *Chandra* (Kouveliotou et al. 2004).

The second clear case of association between a GRB and a SN was that of GRB 030329 and SN 2003dh. This was also a rather nearby GRB ($z = 0.1687$), but in this case it was a normal one. After extraction from the strong afterglow light, the SN turned out to be very similar to SN 1998bw (Stanek et al. 2003; Hjorth et al. 2003; Matheson et al. 2003; Lipkin et al. 2004). A study of the LC and the spectra confirmed that SN 2003dh was also a very energetic SN Ic, with overall properties similar to those of SN 1998bw, although perhaps somewhat less extreme [$E \sim 3.5 \times 10^{52}$ ergs, $M_{\rm ej} \sim 8\ M_{\odot}$, $M(^{56}{\rm Ni}) \sim 0.35\ M_{\odot}$, $M_{\rm ZAMS} \sim 35\ M_{\odot}$; Mazzali et al. 2003; Deng et al. 2005]. A late-time spectrum of SN 2003dh also shows a narrow [O i] and broad [Fe ii] lines (Bersier et al. 2006).

Given this evidence, it could be expected that the third closest GRB ever detected (GRB 031203 at $z = 0.1055$) should also reveal SN signatures. The GRB was distinctly weaker than average, but stronger than GRB 980425. Very strong reddening and

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TABLE 1
Late-Time Photometry

Mean Date (UT)	Exposure Time (minutes)	Seeing (arcsec)	Filter	Instrument	Magnitude
2004 May 22.02..............	2 × 2	0.6	*R*	FORS1	20.44 ± 0.02
2004 May 22.02..............	2 × 2	0.6	*I*	FORS1	19.40 ± 0.04

a bright galaxy background made the detection of the SN very difficult. Nevertheless, a SN was eventually detected photometrically (Tagliaferri et al. 2004; Thomsen et al. 2004; Gal-Yam et al. 2004; Cobb et al. 2004) and spectroscopically (Malesani et al. 2004, hereafter MTC04). Perhaps not surprisingly, SN 2003lw showed a spectrum similar to those of SNe 1998bw and 2003dh.

The determination of the properties of SN 2003lw requires reliable measurements of its LC and spectra. This is made difficult by contamination from host galaxy light. Therefore, we have reobserved the field after the SN faded in order to quantify the contribution of the host galaxy and subtract it out properly.

In this paper we present newly reduced data for SN 2003lw, derive the SN LC, and model it and the spectra. Using highly energetic SN Ic models similar to those used for SN 1998bw, we determine the most likely reddening and derive the properties of SN 2003lw.

2. LATE-TIME OBSERVATIONS

In order to subtract the host galaxy light as accurately as possible, late-time photometry[14] and spectroscopy of the host galaxy were performed on 2004 May 22 ($\approx$5 months after the GRB) with the ESO VLT-UT1 (Antu) and FORS2, at a time when the SN contribution to the total light should be negligible. The photometry is reported in Table 1. Data reduction and analysis were performed following standard procedures, using the Eclipse and GAIA packages. The SN aperture photometry was calibrated using new field photometry of several standard fields. Photometric analysis shows only a slight fading (0.04 ± 0.02 mag in the *R* band) with respect to 2004 March (MTC04).

Spectroscopy was performed with grism 150I (6000–10000 Å). The net exposure time was 45 minutes, and the seeing was 0.″6. The data were reduced using standard IRAF routines. This new "galaxy only" spectrum was used to remove the host contribution from a red 150I grism spectrum acquired on 2003 December 20, which was not presented in MTC04 because of uncertainties in host galaxy subtraction. Flux calibration was achieved observing two standard stars, LTT 3864 and LTT 3218. Consistent results were obtained for the two cases. In order to ensure relative calibration of the spectra of 2003 December and 2004 May we computed the flux of the galaxy emission lines in the different observations and introduced a small correction to make them match exactly. The entire set of Very Large Telescope (VLT) spectroscopic observations of SN 2003lw is reported in Table 2.

3. THE BOLOMETRIC LIGHT CURVE OF SN 2003lw

In order to derive the properties of SN 2003lw through modeling, it is necessary to construct the bolometric LC from the observations. This requires careful subtraction of the host galaxy contribution. Photometry was in fact dominated by the host light, so the shape and brightness of the reduced SN LC are sensitive to the adopted host brightness. Reliable host photometry can only be obtained when the SN has faded sufficiently. Our new data were obtained sufficiently late that we can assume this is the case.

We adopted as host galaxy magnitudes the *R* and *I* measurements obtained on 2004 May 22 (see Table 1). These fluxes are both lower than those measured in March in these bands (MTC04), but the difference is at most 2 σ, indicating that the SN contributed by no more than 3% to the integrated flux in these bands already in 2004 March (as a comparison, SN 1998bw became 1 mag fainter over the same time interval; Patat et al. 2001).

As for the host *V*-band magnitude, we had to base our estimate on the last available *V*-band measurement, which was taken only $\sim$3 months after the SN explosion ($V = 20.54 \pm 0.05$, 2004 March 2) and is probably still affected by the SN. We therefore considered that the SN+host magnitude declined by 0.2 mag over the 2 months between late December 2003 and 2004 March 2. A SN Ic similar to SN 1998bw declines by $\sim$2.2 mag over that time interval. This suggests that SN 2003lw still makes a contribution of $\sim$3% to the total light on 2004 March 2. Therefore we adopted a value $V(\text{host}) \simeq 20.57 \pm 0.05$. Figure 1 shows the *R*-band LC of SN 2003lw after subtracting the host galaxy contribution, compared to the one of SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999).

Since NIR templates for SN 1998bw are not available, we derived a host magnitude starting from the magnitudes measured in 2004 February (MTC04) and corrected them as above, assuming that the SN makes a contribution in *J*, *H*, and *K* similar to that in the *V* band. Accordingly, we use host galaxy magnitudes $J = 18.28 \pm 0.05$, $H = 17.58 \pm 0.04$, and $K = 16.69 \pm 0.06$. These values are in fair agreement with those reported by Prochaska et al. (2004), Gal-Yam et al. (2004), and Cobb et al. (2004).

One of the major uncertainties in the calibration of the photometry of SN 2003lw is the reddening. This is large, and may have both a Galactic and a host component. Schlegel et al. (1998) report for the direction of GRB 031203/SN 2003lw a Galactic extinction $E_G(B-V) = 1.04$. Prochaska et al. (2004) note that this value may be highly uncertain and suggest a value $E_G(B-V) = 0.78$ as a lower limit.

Spectrum synthesis favors a total reddening $E_{G+H}(B-V) = 1.07 \pm 0.05$ (see § 5). This is $\sim$0.1 smaller than the value obtained by Prochaska et al. (2004) and is formally consistent with the Galactic value of Schlegel et al. (1998) and no host extinction. Lack of significant extinction in GRB host galaxies is

TABLE 2
Spectroscopy of SN 2003lw

Mean Date (UT)	Exposure Time (minutes)	Seeing (arcsec)	Grism	Instrument
2003 Dec 20.30	2 × 15	0.3	150I	FORS2
2003 Dec 20.35	2 × 45	0.3	300V	FORS2
2003 Dec 30.30	2 × 45	0.5	300V	FORS1
2004 Mar 02.12	4 × 30	0.6	300V	FORS1
2004 May 22.00..........	3 × 15	0.6	150I	FORS1

[14] Based on observations performed at ESO-Paranal under program ID 073.D-0255.

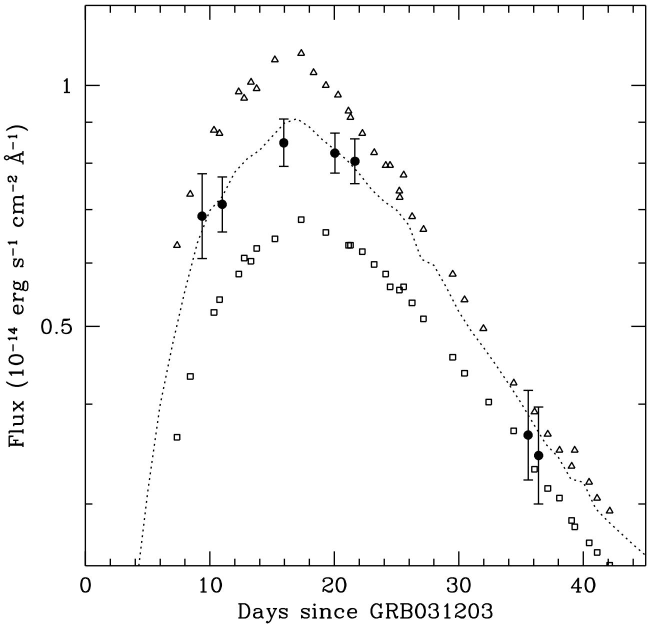

FIG. 1.—*R*-band light curve (LC) of SN 2003lw, galaxy-subtracted and time-stretched by a factor of 0.9 (*filled dots*), compared to the *V* (*triangles*) and *R* (*squares*) LCs of SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999). Because of the redshift, the *R*-band LC of SN 2003lw is equivalent to rest-frame 6000 Å. The equivalent 6000 Å LC of SN 1998bw, obtained by interpolating the *V* and *R* LCs, is shown as a dotted line. The LC of SN 2003lw has been shifted in flux by an arbitrary amount (a factor of 900) to match the corresponding 6000 Å LC of SN 1998bw. The shape of the "time-compressed" LC of SN 2003lw matches well that of SN 1998bw.

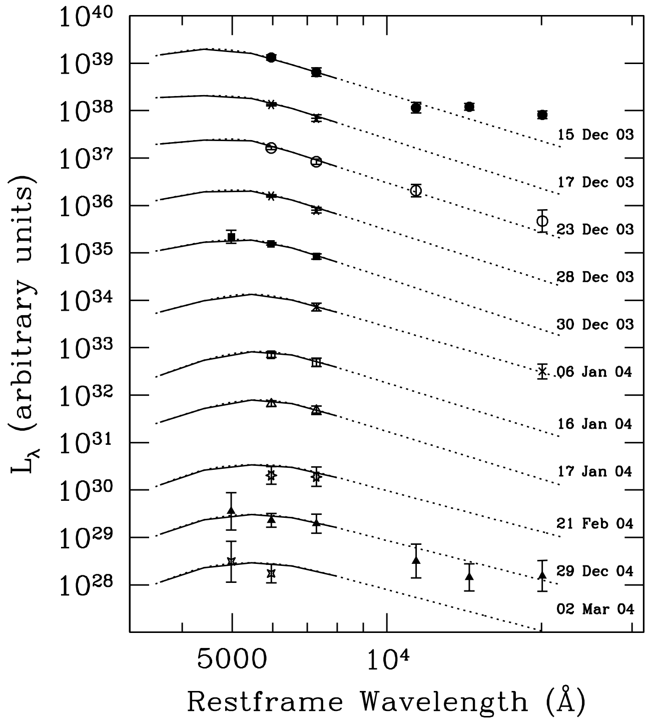

FIG. 2.—Broadband spectra (SEDs) of SN 2003lw corrected for Galactic and host reddening. These were computed using $H_0 = 72$ km s^{-1} Mpc^{-1} (Spergel et al. 2003) and a standard cosmology ($\Omega_\Lambda = 0.72$, $\Omega_M = 0.28$), which yields a distance to SN 2003lw of 475 Mpc (i.e., a distance modulus $\mu = 38.38$). Only for the fluxes corresponding to the first epoch (top spectrum) are the *y*-axis units physical (ergs s^{-1} Å^{-1}). The subsequent spectra, each represented by a different symbol, have been spaced apart by factors of 10, for clarity. The solid curves show the *UBVRI* SEDs of SN 1998bw, dereddened for $E(B-V) = 0.016$ (Nakamura et al. 2001), reconstructed at the phases corresponding to the epochs of the SN 2003lw spectra and multiplied by a constant factor of 1.3 to match the SN 2003lw spectra. The dotted curves are the IR extrapolations of the SN 1998bw optical spectra.

indeed often reported (e.g., Watson et al. 2006b and references therein). However, following Prochaska et al. (2004), we adopt $E_G(B-V) = 0.78$ and $E_H(B-V) = 0.25$, which results from the difference between $E_{G+H}(B-V) = 1.07$ and $E_G(B-V) = 0.78$. Given that extinction laws of GRB hosts are uncertain and that an SMC-type law may be favored with respect to a Milky Way–type law (MW; see Watson et al. 2006b), we computed the intrinsic extinction suffered by the SN light under the two assumptions of a MW-type (Cardelli et al. 1989) and an SMC-type extinction curve (Pei 1992) in the NIR and optical ranges. For $E_H(B-V) = 0.25$ the difference in the amount of extinction is at most 5% in these wavelength ranges, which is well within our uncertainties. Therefore we adopted a MW extinction curve. The value of $E_H(B-V)$ we use here is likely to represent the maximum possible value.

In order to evaluate the bolometric LC of SN 2003lw we then proceeded as follows. First, we verified that SNe 2003lw and 1998bw have similar spectra. We constructed the dereddened spectral energy distribution (SED) of SN 2003lw at every epoch corresponding to an *R*- and/or *I*-band measurement using the available simultaneous or quasi-simultaneous optical and NIR photometry. We interpolated the dereddened SEDs of SN 1998bw [using $E(B-V) = 0.016$ from Nakamura et al. 2001] to the phases of the SEDs of SN 2003lw, taking into account the 1.1 time stretch factor. The SEDs of SN 2003lw are shown in Figure 2 together with the reconstructed SEDs of SN 1998bw. In order to match the two SNe in the optical, the SEDs of SN 1998bw were scaled up by a factor of 1.3. This represents the difference in intrinsic luminosity between the two SNe.

Since the data of SN 1998bw do not extend to the IR, we extrapolated linearly the red part of the optical SED. The agreement between the SEDs of the two SNe is very good, except for the *K*-band point at the first epoch. Therefore, since the SEDs of SN 1998bw extend to bluer wavelengths than those of SN 2003lw, the "UVOIR" bolometric magnitudes of SN 2003lw were computed by integrating the flux under the SN1998bw templates between rest-frame 3600 and 22200 Å.

The integrated UVOIR LCs of the two SNe are shown in Figure 3. The LC of SN 2003lw is broader than that of SN 1998bw by a factor of ~1.1, but it is very similar to it in shape and is more luminous by ~0.3 mag. This is a smaller difference than what was quoted in MTC04 and Thomsen et al. (2004), and it is mostly the result of adopting a smaller reddening to SN 2003lw. Considering the significant systematic uncertainties (~0.15 mag from the reddening to both SNe, ~0.10 mag from possible peculiar velocities affecting the distance to SN 1998bw), the combined systematic error on the relative luminosity is ~0.2 mag.

4. MODELING THE SN LIGHT CURVE

We based synthetic LC calculations on the one-dimensional SN LC synthesis code (Iwamoto et al. 2000) that was used to model other Type Ic SNe (e.g., Nakamura et al. 2001; Mazzali et al. 2002, 2003). The code solves the energy and momentum equations of the radiation plus gas in the comoving frame, and it is accurate to first order in *v*/*c*. Electron densities and the electron scattering opacity are determined from the Saha-Boltzmann equation. We adopted the approximation proposed by Gómez-Gomar & Isern (1996) for the Eddington factors and fitted the TOPS opacities (Magee et al. 1995) to find an empirical relationship between the Rosseland mean and the electron scattering opacity. The energy deposition from radioactive decays was calculated

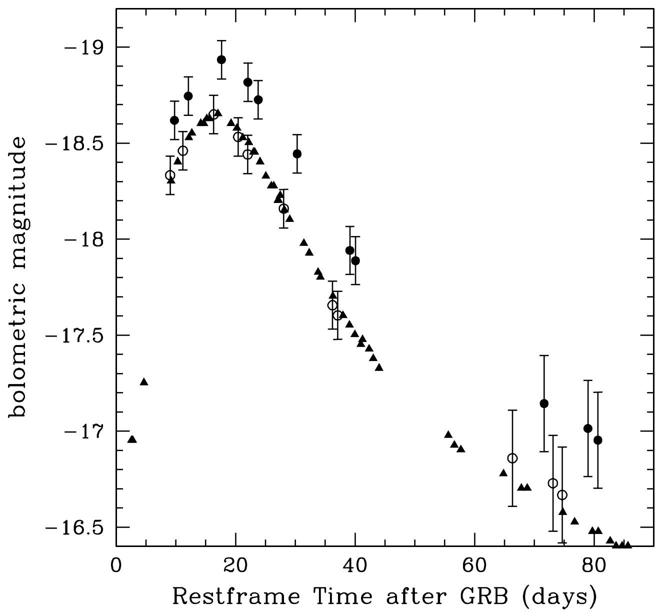

FIG. 3.— Bolometric UVOIR LCs of SNe 2003lw (*filled dots*) and 1998bw (*triangles*). The LC of SN 1998bw was computed for a distance modulus $\mu = 32.76$ and $E(B-V) = 0.016$, that of SN 2003lw for $\mu = 38.38$, $E_G(B-V) = 0.8$, and $E_H(B-V) = 0.25$. The open circles show the LC of SN 2003lw stretched by a factor of 0.9 and shifted in flux to match the LC of SN 1998bw. Error bars do not include a systematic uncertainty of ± 0.2 mag (§ 3).

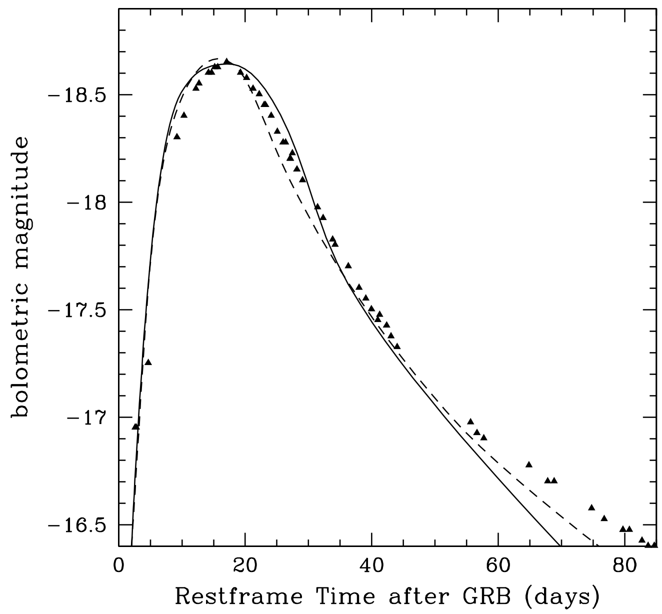

FIG. 4.— Models for the UVOIR bolometric LC of SN 1998bw (*triangles*): the solid line shows model CO138E50; the dashed line shows the two-component model.

with a gray γ-ray transfer code, assuming an absorptive opacity of $0.05 Y_e$ cm^2 g^{-1} (Swartz et al. 1995). The γ-ray energy source function was evaluated from the latest nuclear data (Firestone et al. 1999).[15]

To test the above assumptions, as well as other modifications we made to the code, we computed the LC of SN 1998bw using model CO138E50, which fits the spectra and LC of SN 1998bw near the LC peak (Nakamura et al. 2001). Model CO138E50 has $M_{\rm ej} = 10.2\ M_\odot$ and $E = 5 \times 10^{52}$ ergs. We also used the two-component model developed by Maeda et al. (2003). This model has a denser core than CO138E50 to mimic the effect of a two-dimensional explosion, and thus it can reproduce better the late-time LC of SN 1998bw. It has $M_{\rm ej} = 10.7\ M_\odot$ and $E = 4.6 \times 10^{52}$ ergs. We updated the SN 1998bw bolometric LC of Patat et al. (2001) to a distance modulus $\mu = 32.76$, corresponding to $H_0 = 72$ km s^{-1} Mpc^{-1}. Both models require a ^{56}Ni mass of $0.41 \pm 0.05\ M_\odot$. The distribution of ^{56}Ni is $0.09\ M_\odot$ below 5000 km s^{-1}, $0.30\ M_\odot$ between 5000 and 23,000 km s^{-1}, and $0.02\ M_\odot$ above 23,000 km s^{-1} for CO138E50 and 0.07, 0.32, and 0.02 $M_\odot$ in the same three zones for the two-component model. These values are consistent with those of Nakamura et al. (2001), once the difference in the adopted distance is considered. The early portion of the LC of SN 1998bw is well reproduced by both models (Fig. 4). However, as expected, the two-component model fits the late-time LC better than CO138E50, confirming the results of Maeda et al. (2003).

As we showed above, the shapes of the bolometric LCs of SNe 1998bw and 2003lw are very similar, but the latter is broader by a factor of 1.1. It is well known that the timescale of the LC near the peak, τ, depends on the ejected mass $M_{\rm ej}$, the kinetic energy E, and the opacity κ as $\tau \propto \kappa^{1/2} M_{\rm ej}^{3/4} E^{-1/4}$ (Arnett 1982). Since the difference between the two SNe is small, we based our calculations on model CO138E50, increasing its density in order to reproduce the broader LC of SN 2003lw. Given the relation above, we increased $M_{\rm ej}$, and consequently E, by a factor of 1.2, leading to $M_{\rm ej} = 12.25\ M_\odot$ and $E = 6 \times 10^{52}$ ergs.

We took the mass and the distribution of ejected ^{56}Ni as free parameters and assumed that the rest of the ejecta consists of 90% O and 10% Si by mass. This simplified composition was adopted because the two spectra we have available for modeling are too early to constrain the composition of the bulk of the ejecta, and also because our model is an approximate one-dimensional reproduction of the probably aspherical ejecta. In addition, we tested the two-component model of SN 1998bw, also scaled up in mass by a factor of 1.2, so that the two-component model for SN 2003lw has $M_{\rm ej} = 12.85\ M_\odot$ and $E = 5.5 \times 10^{52}$ ergs.

Modeling the LC alone does not yield a unique result: simultaneous modeling of the spectra is required, and this is performed in § 5. An additional complication in the case of SN 2003lw is the uncertain reddening. We used a total reddening $E_{G+H}(B-V) = 1.07$, derived from spectral models as discussed in § 5.

The shape of the bolometric LC of SN 2003lw is not much affected by the choice of reddening. Our main model parameters, $M_{\rm ej}$ and E, affect the LC shape and do not change for different reddenings. The overall brightness of course does change, but it can be reproduced using different amounts of ejected ^{56}Ni.

Figure 5 shows the bolometric LC of SN 2003lw and the best-fitting synthetic LCs obtained scaling CO138E50 and adjusting the ^{56}Ni distribution. The total ^{56}Ni mass is $\sim 0.54\ M_\odot$. As in the case of SN 1998bw, we adopted a distribution of ^{56}Ni with an inner zone at $v < 5000$ km s^{-1} and an outer zone between 5000 and 23,000 km s^{-1}, and we assumed uniform ^{56}Ni abundance within each zone. The best-fitting ^{56}Ni distribution is 0.12 $M_\odot$ in the inner zone and 0.42 $M_\odot$ in the outer zone. Unlike the case of SN 1998bw, lack of early photometry phase makes it impossible to tell whether ^{56}Ni was mixed to the highest velocities, so we did not introduce ^{56}Ni above 23,000 km s^{-1}.

The synthetic LC of the scaled two-component model is also shown in Figure 5. The ^{56}Ni mass in this model is also 0.54 $M_\odot$, of which 0.10 $M_\odot$ is below $v < 5000$ km s^{-1} and 0.44 $M_\odot$ is above. The two-component model fits better than CO138E50 after maximum, confirming that the dense core of these models is efficient in absorbing γ-rays and influences the LC after peak.

[15] See also the LBNL isotopes project Web site: http://ie.lbl.gov/toi.

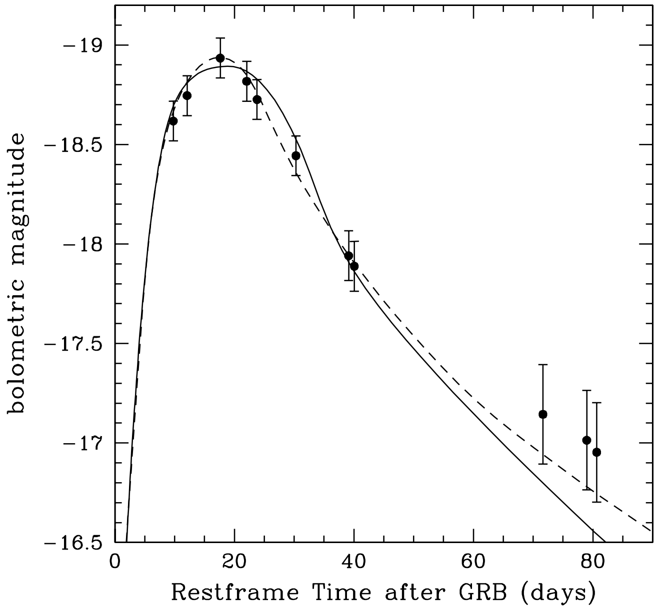

FIG. 5.— Models for the UVOIR bolometric LC of SN 2003lw (*dots*): the solid line shows the rescaled model CO138E50; the dashed line shows the two-component model.

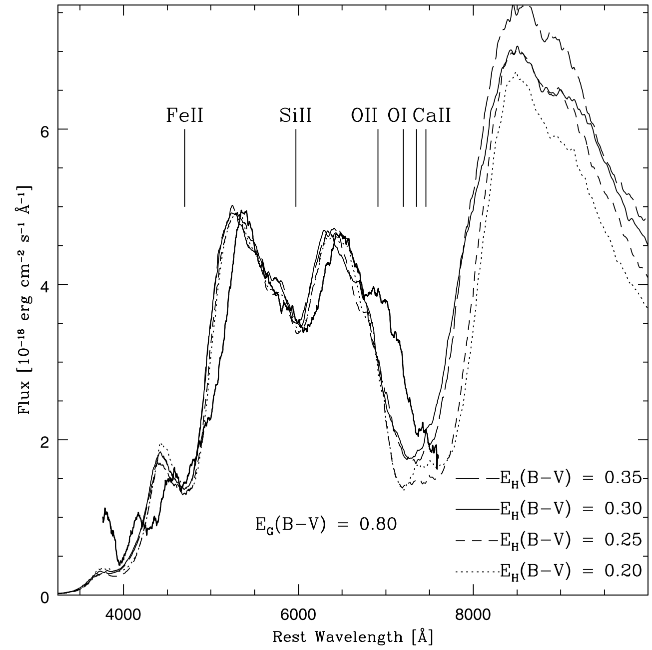

FIG. 6.— VLT spectrum of SN 2003lw obtained on 2003 December 20 (*thick line*), compared to four synthetic spectra, computed with $E_G(B-V) = 0.8$ and $E_H(B-V) = 0.2$ (*dotted line*), 0.25 (*short-dashed line*), 0.3 (*thin solid line*), and 0.35 (*long-dashed line*), respectively.

Since the γ-ray deposition efficiency is increased by adding the inner dense core, a ^{56}Ni mass similar to that used for the rescaled CO138E50 model is sufficient to sustain the higher integrated luminosity of the LCs of the two-component models.

From the above studies, we cannot select between scaled CO138E50 and the scaled two-component model. The synthetic LCs differ before maximum, but we do not know the exact shape of the premaximum SN 2003lw LC. Also, this phase is very sensitive to the ^{56}Ni distribution. Moreover, the two spectra available are too early to show evidence of a dense core, unlike the cases of other previously studied HNe (SNe 1997ef, 1998bw, and 2002ap; Mazzali et al. 2000, 2002; Maeda et al. 2003), and the LC coverage does not extend to sufficiently late times to apply the two-component models of Maeda et al. (2003). It is therefore unfortunately impossible to apply the two-dimensional models of the spectra and the LC as was possible for SN 1998bw (Maeda et al. 2002). We would however expect that since SN 2003lw was similar to SN 1998bw, its late-time properties would also be best described by a highly aspherical explosion viewed close to the jet axis.

5. SPECTRAL MODELING

Because of the brightness of the host galaxy it was only possible to obtain SN spectra at two epochs near maximum: 2003 December 20 and 30, corresponding to rest-frame epochs of 16 and 24 days past explosion, respectively. Here we add the red 150I grism VLT spectrum of 2003 December 20 to the two blue 300V grism spectra shown in MTC04. This is useful because it is less sensitive to reddening. It shows a very strong P Cygni profile, probably a blend of Ca II IR and O I λ7772, a typical HN signature (e.g., Mazzali et al. 2002).

We computed synthetic spectra with our Monte Carlo code (Mazzali & Lucy 1993; Lucy 1999; Mazzali 2000) for these two epochs. Following the results of the LC modeling, we used model CO138E50 rescaled in mass by a factor $f = 1.2$. We did not use the rescaled two-component model, as it only differs in the innermost part, which is not probed by the spectra near maximum. Our models can be used to constrain the total reddening and have some leverage on the relative Galactic and host reddening since the two galaxies are separated by $z = 0.1055$. We adopted $E_G(B-V) = 0.8$ as a lower limit, attributed the remaining reddening to the host, and tested different values of rest-frame $E_H(B-V)$.

In Figure 6 we show the December 20 spectrum and four synthetic spectra, computed for $E_H(B-V) = 0.2, 0.25, 0.3$, and 0.35. The main input parameters of the models and the properties of the synthetic spectra are summarized in Table 3. Both Galactic and host reddening were computed using the Cardelli et al. (1989) law. Obviously, the model luminosity increases with increasing reddening. In all models the composition is dominated by oxygen (~70% by mass) and neon (~20%). ^{56}Ni is only ~2%–3% by mass, and silicon is even less, ~1%–2%. This composition is slightly different from that used for LC modeling. Including both Ne and O is important for the spectrum synthesis, while the synthetic LC is not significantly affected by replacing Ne with O. As reddening decreases, the abundance of ^{56}Ni also decreases, while that of oxygen increases, resulting in a progressively stronger O I absorption near 7000 Å.

All models are very similar in the blue, where the main absorption features are due to Fe II, Co II, and Ti II lines (the big trough at 4000–4500 Å), and in the V region, which is dominated by lines of Si II and S II. However, the behavior in the red, where the strong Ca II–O I P Cygni line shows prominently, is rather different. The model with $E_H(B-V) = 0.2$ shows too much absorption in this

TABLE 3
MODELS FOR THE DECEMBER 20 SPECTRUM

Model	$E_H(B-V)$	log L (ergs s^{-1})	v_{ph} (km s^{-1})	V	M_V	M(Bol)
1............	0.20	43.01	17,250	21.88	−19.43	−18.82
2............	0.25	43.09	18,500	21.90	−19.58	−19.03
3............	0.30	43.16	18,150	21.88	−19.75	−19.20
4............	0.35	43.26	19,000	21.83	−19.96	−19.45

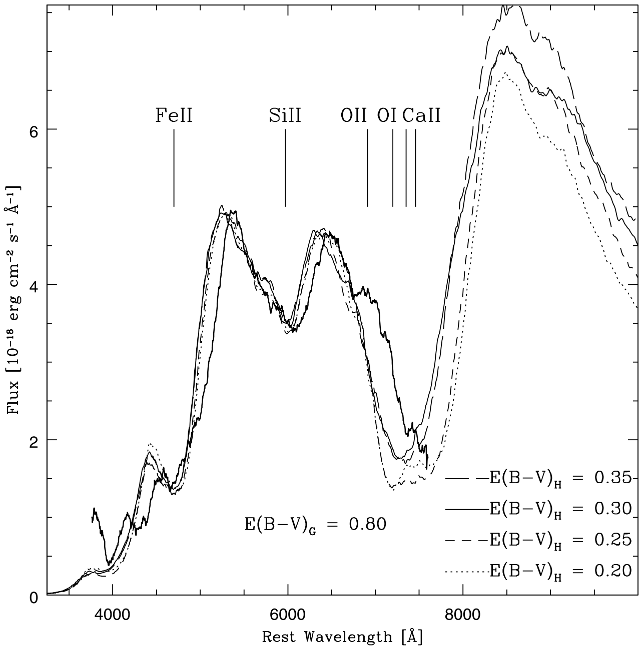

FIG. 7.— VLT spectrum of SN 2003lw obtained on 2003 December 30 (*thick line*), compared to four synthetic spectra, computed with $E_G(B-V)=0.8$ and $E_H(B-V)=0.2$ (*dotted line*), 0.25 (*short-dashed line*), 0.3 (*thin solid line*), and 0.35 (*long-dashed line*), respectively.

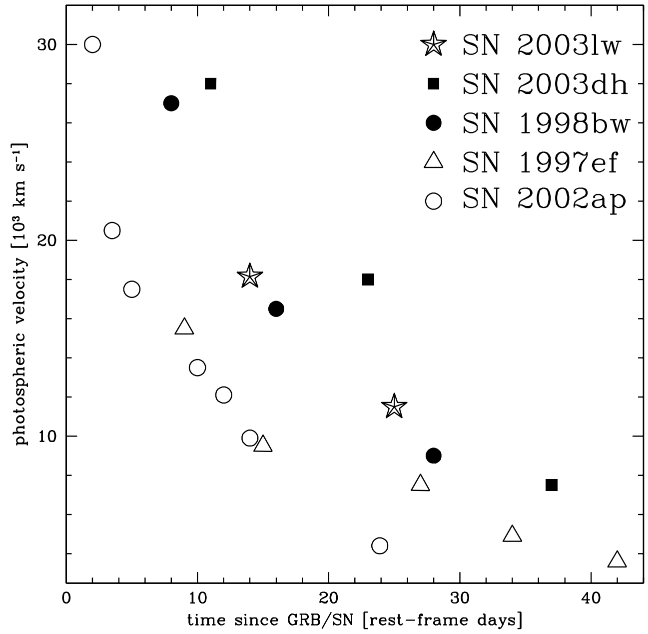

FIG. 8.— Evolution of the photospheric velocity in SN 2003lw (*stars*) and in a number of broad-lined SNe Ic. The references for the data are as follows: SN 1997ef: Iwamoto et al. (2000); SN 1998bw: Iwamoto et al. (1998); SN 2002ap: Mazzali et al. (2002); SN 2003dh: Mazzali et al. (2004).

feature. This is a consequence of the high abundance of oxygen. In this model, in fact, the abundances of the heavier elements that give rise to the lines in the blue are lower than they are in models with higher reddening, while the abundance of oxygen is higher. The models with $E_H(B-V)=0.25$, 0.3, and 0.35 all reproduce the Ca II–O I absorption well, but the model with the highest reddening has a large luminosity, and consequently a large photospheric velocity, so that the spectral lines are too red, and the model is of lower quality.

Models for the December 30 spectrum are shown in Figure 7. Because of the smaller wavelength coverage at this epoch, it is not easy to discriminate among the models, all of which look reasonably good. The input values are listed in Table 4. The abundances are similar to those used for the December 20 spectrum, but ^{56}Ni (and decay products) is reduced by a factor of ~2. This shows that more ^{56}Ni was produced at higher velocities, contributing to the earlier spectrum, and confirms the scenario of an aspherical explosion. It is unfortunate that the earliest spectrum is only at peak; otherwise, we might have been able to determine more accurately the ^{56}Ni abundance in the outermost, fastest moving layers. All models fit the blue part of the spectrum nicely, but those with $E_H(B-V)=0.25$ and 0.3 seem to be the best in the O I–Ca II region, at least if we trust the red end of the spectrum. As was the case for the December 20 models, the oxygen abundance is higher for models with lower reddening, causing

TABLE 4

MODELS FOR THE DECEMBER 30 SPECTRUM

Model	$E_H(B-V)$	log L (ergs s^{-1})	v_{ph} (km s^{-1})	V	M_V	M(Bol)
1............	0.20	42.85	10,000	22.27	−19.04	−18.42
2............	0.25	42.91	10,500	22.30	−19.17	−18.57
3............	0.30	43.00	11,500	22.25	−19.37	−18.80
4............	0.35	43.09	10,625	22.24	−19.55	−19.02

the exceedingly strong O I absorption near 7200 Å. Therefore, given our assumed Galactic reddening, $E_G(B-V)=0.8$, we favor a value of the host reddening $E_H(B-V)\sim 0.25\pm 0.05$. This results in a total reddening of $E_{H+G}(B-V)\sim 1.07\pm 0.05$ when the redshift of the host is taken into account. Since the total reddening is the quantity that is best constrained by our models, our result is also consistent with the Schlegel et al. (1998) Galactic reddening and no host extinction. With this value of the reddening, the absolute magnitude of SN 2003lw on 2003 December 20 is −19.03, which is consistent with our LC analysis (Table 3).

6. DISCUSSION

The properties of SN 2003lw are very similar to those of the other well-observed GRB-SNe. Given our chosen values of the host reddening, the rescaled explosion model that best fits both the light curve (LC) and the spectra of SN 2003lw has an $E\sim 6\times 10^{52}$ ergs and $M_{ej}\sim 13\ M_\odot$. From the value of M_{ej}, the inferred mass of the progenitor of SN 2003lw is ~40–50 $M_\odot$. These values are similar to, although somewhat larger than, those of SN 1998bw. SN 2003lw follows the positive correlation between E, $M(^{56}$Ni), and progenitor mass that appears to hold for SNe Ic (Nomoto et al. 2004, 2005). As in the case of SN 1998bw, SN 2003lw is also likely to have left behind a black hole remnant.

Figure 8 shows the time evolution of the photospheric velocity as determined from spectral modeling for the three well-studied GRB-SNe and for other broad-lined SNe Ic that did not show an accompanying GRB. The three GRB-SNe have the highest values, SN 2003dh being somewhat higher than the other two. Both SNe Ic, SN 1997ef and SN 2002ap, have much lower photospheric velocities.

It must be stressed that the estimated values of the explosion parameters of SN 2003lw are necessarily approximate. As we discussed, the estimated peak brightness of the SN, and hence the derived ^{56}Ni mass, depends sensitively on the uncertain galaxy subtraction and the assumed reddening. Moreover, the estimate of E is based on spherically symmetric models of the explosion. If

TABLE 5

GRB Energetics

GRB (1)	T (s) (2)	S_γ (10^{-6} ergs cm^{-2}) (3)	Range (keV) (4)	Instrument (5)	Reference (6)	E_{iso}[a] (ergs) (7)
980425.................	31	2.8 ± 0.5	40–700	*BeppoSAX* GRBM	1	4.3×10^{47}
	23	4.4 ± 0.4	24–1820	*CGRO* BATSE	2	
030329.................	35	65.7 ± 0.5	2–30	*HETE* FREGATE	3	7.7×10^{51}
	23	118.2 ± 1.6	30–400	*HETE* FREGATE	3	
	23	183.9 ± 1.7	2–400	*HETE* FREGATE	3	
031203.................	40	2.0 ± 0.4	20–200	*INTEGRAL* IBIS	4	4.9×10^{49}

[a] Total γ-ray output for GRB, assuming isotropic emission.

References.—(1) Pian et al. 2000; (2) Galama et al. 1998; (3) Vanderspek et al. 2004; (4) Sazonov et al. 2004.

asymmetries were taken into account, most likely in the form of an aspherical explosion, as was possible for the much better studied case of SN 1998bw, it is very likely that the value of E would be reduced. In the case of SN 1998bw an estimate based on a spherical model suggested that the true kinetic energy is smaller by about a factor of 5 with respect to E, yielding a true $E \sim 10^{52}$ ergs (Maeda et al. 2002). Such a study was made possible for SN 1998bw by the availability of late-time spectrophotometry, which unfortunately cannot be obtained for SN 2003lw since the bright host galaxy outshines the SN. The relation between the true and isotropic equivalent energies depends sensitively on both the asphericity of the explosion and our viewing angle. If these were not too different for the three GRB-SNe, as is likely, then the true E of SN 2003lw may be reduced by a similar factor, to $\sim 1.2 \times 10^{52}$ ergs, and that of SN 2003dh to $\sim 7 \times 10^{51}$ ergs. Even after such a major reduction, the E of the three GRB-SNe remains very large compared to that of typical SNe, earning them the name "hypernovae" (HNe).

Perhaps the most remarkable aspect is that although the properties of the three GRB-SNe vary by at most $\pm 30\%$, those of the related GRBs (γ- and X-ray energy output) cover ~ 4 orders of magnitude, GRB 030329 being almost as energetic as a normal GRB, GRB 031203 a factor of 100 lower, and GRB 980425 a factor of 100 lower still. The durations, γ-ray fluences, and relative energy ranges for the three GRBs are reported in Table 5. The γ-ray outputs of the three GRBs (col. [7]) were computed according to

$$E = \frac{4\pi d^2 S_\gamma}{1+z}. \quad (1)$$

In the above equation d is the distance, S_γ is the fluence, and z is the redshift of the GRB. We assumed isotropic emission. Since the GRBs were detected by different instruments, their fluences (col. [3]) refer to different energy ranges. However, these ranges do not differ much, and so we did not reduce the γ-ray fluxes to a common rest-frame energy range. The properties of the GRB-SNe are summarized in Table 6.

This conundrum may be interpreted in two ways. One is that we may be seeing an intrinsically similar phenomenon under different viewing angles. GRB 030329/SN 2003dh may be viewed almost pole-on, while the orientation of GRB 980425/SN 1998bw may be sufficiently off-axis ($\sim 15°$–$30°$; Maeda et al. 2002, 2006) that the detected GRB is significantly weaker. GRB 031203/SN 2003lw may lie somewhere in between (Ramirez-Ruiz et al. 2005). If this is indeed the case, then the γ-ray properties are a very strong function of angle (e.g., $E_\gamma \propto \theta^{-4}$). In this scenario, where line-of-sight inclination is a natural free parameter, the optical properties of the SN are not much influenced by this relatively small spread in viewing angles, since the asymmetry in the SN is much less pronounced than it is in the GRB (Maeda et al. 2002). Larger spectral differences require larger inclination angles and are best seen in the nebular phase (Mazzali et al. 2005; Maeda et al. 2006).

The other possibility is that there is a dispersion in the properties of the relativistic ejecta for SNe with otherwise very similar characteristics. This may well be, especially if we consider that the relativistic energies at play in the GRB phenomenon ($\sim 10^{47}$–10^{51} ergs) are small compared to the kinetic energy involved in the SN event (from $\sim 10^{51}$ ergs for a normal SN to $\sim 10^{52}$ ergs for a HN) and to the presumably even larger neutrino energies ($\sim 10^{53}$–10^{54} ergs) if there is a bounce (Deng et al. 2005).

However, the inferred spread of properties of the SNe, albeit only of the order of $\sim 30\%$, is seen not only in E and M_{ej}, but also in less orientation-dependent quantities such as the mass of ^{56}Ni, and therefore it is almost certainly real. Most likely both intrinsic differences and orientation effects are present. So, while the observed γ-ray energy of GRB 980425 was so low that it may require

TABLE 6

Properties of GRB-SNe

GRB/SN	E (10^{51} ergs)	$M(^{56}\mathrm{Ni})$ ($M_\odot$)	M_{ej} ($M_\odot$)	M_{ZAMS} ($M_\odot$)	References
GRB 980425/SN 1998bw.............	50 ± 5	0.38–0.48	10 ± 1	35–45	1, 2, 3
GRB 030329/SN 2003dh	40 ± 10	0.25–0.45	8 ± 2	25–40	4, 5
GRB 031203/SN 2003lw	60 ± 10	0.45–0.65	13 ± 2	40–50	6

References.—(1) Iwamoto et al. 1998; (2) Nakamura et al. 2001; (3) Maeda et al. 2003; (4) Mazzali et al. 2003; (5) Deng et al. 2005; (6) this paper.

an intrinsically weak GRB with normal spectral properties, the true energy may be higher than estimated, since the GRB was viewed off-axis, as suggested by SN nebular line profile studies.

The case of GRB 031203 is similarly uncertain: on the basis of its X-ray to γ-ray flux ratio, it was reported to be an X-ray flash (Watson et al. 2004, 2006a). However, Sazonov et al. (2004) suggested that it is a classical GRB based on the shape of the γ-ray spectrum. On the basis of radio calorimetry and the absence of the signature of an off-axis afterglow, Sazonov et al. (2004) and Soderberg et al. (2004) suggest that it is an intrinsically underluminous event. However, Ramirez-Ruiz et al. (2005) model the event as a standard-energy, off-axis GRB. Since nebular-phase spectra of SN 2003lw are not available, it is unfortunately impossible to estimate the geometry of the explosion and the viewing angle.

Although it is now clear that long-duration GRBs and energetic, broad-lined SNe Ic (HNe) are related (Galama et al. 1998; Hjorth et al. 2003; MTC04; Podsiadlowski et al. 2004), the physical link between the relativistic event and these SNe remains uncertain. Further uncontroversial occurrences of GRB-SN association will hopefully clarify the issue.

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