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ON THE LIGHT CURVE AND SPECTRUM OF SN 2003dh SEPARATED FROM THE OPTICAL AFTERGLOW OF GRB 030329

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ABSTRACT

The net optical light curves and spectra of the supernova (SN) 2003dh are obtained from the published spectra of GRB 030329, covering about 6 days before SN maximum to about 60 days after. The bulk of the *U*-band flux is subtracted from the observed spectra using early-time afterglow templates, because strong line blanketing greatly depresses the UV and *U*-band SN flux in a metal-rich, fast-moving SN atmosphere. The blue-end spectra of the gamma-ray burst (GRB) connected hypernova SN 1998bw is used to determine the amount of subtraction. The subtraction of a host galaxy template affects the late-time results. The derived SN 2003dh light curves are narrower than those of SN 1998bw, rising as fast before maximum, reaching a possibly fainter maximum, and then declining $\sim$1.2–1.4 times faster. We then build *UVOIR* bolometric SN light curve. Allowing for uncertainties, it can be reproduced with a spherical ejecta model of $M_{\rm ej} \sim 7 \pm 3\ M_\odot$, $E_K \sim 3.5 \pm 1.5 \times 10^{52}$ ergs, with $E_K/M_{\rm ej} \sim 5$ following previous spectrum modeling, and $M(^{56}{\rm Ni}) \sim 0.4^{+0.15}_{-0.1}\ M_\odot$. This suggests a progenitor main-sequence mass of $\sim$25–40 $M_\odot$, lower than SN 1998bw but significantly higher than normal Type Ic SNe and the GRB-unrelated hypernova SN 2002ap.

Subject headings: gamma rays: bursts — supernovae: general — supernovae: individual (SN 2003dh)

1. INTRODUCTION

Supernova SN 2003dh was discovered in the spectra of the optical transient (OT) of the nearby gamma-ray burst GRB 030329 ($z = 0.1685$; e.g., Stanek et al. 2003b; Hjorth et al. 2003), providing a strong confirmation that long GRBs originate from core collapse of very massive stars (e.g., the "collapsar" model; MacFadyen & Woosley 1999). Previous clear evidence of the GRB-SN connection, although not as direct, was the temporal and spatial coincidence between SN 1998bw and another nearby GRB 980425 ($z = 0.0085$; Galama et al. 1998). SN 1998bw displayed unusually broad spectral features that require a high explosion energy to explain, more than 10 times that of an ordinary SN (Iwamoto et al. 1998; Woosley et al. 1999), and because of this it was termed a "hypernova" (Nomoto et al. 2004). The spectral features of GRB 030329/SN 2003dh have also been shown to be hypernova-like (Stanek et al. 2003b; Kawabata et al. 2003; Hjorth et al. 2003; Matheson et al. 2003; Kosugi et al. 2004).

Various efforts have been made to separate the SN light from the underlying optical afterglow (OA) of GRB 030329, yielding different results (see Lipkin et al. 2004 and references therein). The difficulty lies in the fact that the brightness of the OA thoroughly eclipsed that of the SN for the first week and kept competing with it for at least 1 month. This is unlike the case of GRB 980425/SN 1998bw, in which an OA was not detected. The problem is further compounded by the contribution of the host galaxy to any spectroscopy and photometry.

Matheson et al. (2003) and Hjorth et al. (2003) used a least-squares fit to decompose their observed spectra of the first month. They adopted the spectra of SN 1998bw and other hypernovae as templates and assumed an OA template using either an early spectrum or a power-law continuum. The similarities of the first-month spectra to those of SN 1998bw were revealed. However, the assumption implied in this method, that each spectrum of SN 2003dh is identical to one or the other of the known hypernovae, cannot be guaranteed a priori. Matheson et al. (2003) found that the light curve (LC) of SN 2003dh also follows that of SN 1998bw (but is fainter by $\sim$0.2 mag), comparing their derived $R_{\rm C}$-band LC to the *V*-band LC of SN 1998bw without calculating real *K*-corrections. Hjorth et al. (2003), on the other hand, obtained a *V*-band LC with a peak $\sim$5 days earlier, slightly brighter at maximum, and declining $\sim$1.4 times faster after maximum than SN 1998bw.

Kosugi et al. (2004) subtracted a host galaxy template from their $\sim$day 40 and $\sim$day 80 spectra, assuming a negligible OA contribution as extrapolated from Matheson et al. (2003). Their SN spectra in the red part seem more similar to another hypernova, SN 1997ef (Mazzali et al. 2000), than to SN 1998bw (see also Kawabata et al. 2003; Mazzali et al. 2003). They found that the decline rate of SN brightness between these two epochs is similar to that of SN 1998bw.

Bloom et al. (2004) and Lipkin et al. (2004) derived the SN LC directly from the OT photometry, without resorting to spectra. Bloom et al. (2004) assumed a SN 1998bw–like LC shape and suggested that SN 2003dh is 1.5 times brighter than SN 1998bw, after correcting for an assumed host-galaxy extinction of $A(V) = 0.3$ mag. However, their photometry was limited to the first 23 days and was well sampled only until day 12, when the SN component was still weak relative to the OA, and hence was unable to constrain the SN LC well. Lipkin et al. (2004), on the other hand, analyzed a dense *BVRI* data set of the OT photometry extending to day 80. They constructed LCs for SN 2003dh by

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time-stretching those of SN 1998bw by a factor of 0.8 and lowering the brightness by 0.3 mag. They implicitly assumed that the color evolution also follows that of SN 1998bw, time-stretched by the same factor.

To address this problem with the view of theoretical modeling, Mazzali et al. (2003) pointed out that a reasonable spectrum of a Type Ic SN or hypernovae, such as SNe Ia, must show a flux deficiency to the blue of ~3600 Å, owing to strong blanketing effects of dense metal lines (e.g., Baron et al. 1999; Mazzali et al. 2000). They attributed the blue flux of the OT spectrum to the OA and used this to pivot the subtraction to obtain the SN spectrum. However, only three spectra at typical epochs were processed and modeled in that paper. The three bolometric points so derived were nonetheless shown to be consistent with a synthetic LC based on spectral models, which peaks ~5 days earlier, has a maximum brightness ~0.35 mag fainter, and at around 1 month, is fainter by ~0.6 mag than SN 1998bw.

It is important that the spectra and LCs of SN 2003dh are correctly derived, specifying the similarities and differences to SN 1998bw and to other Type Ic SNe and hypernovae, whether GRB-related or not. Recently, another nearby GRB-SN association was discovered, i.e., GRB 031203/SN 2003lw ($z = 0.1055$; e.g., Thomsen et al. 2004; Malesani et al. 2004). Interestingly, SN 2003lw was also claimed to be similar to SN 1998bw, although the observations were dominated by the light from the host galaxy, and the SN suffered from serious extinction. Other observers emphasized the differences with respect to SN 1998bw (Cobb et al. 2004; Gal-Yam et al. 2004). Other cases of possible SNe in GRBs have been reported, virtually all of them based on the detection of a SN 1998bw–like "bump" in the OT LC (e.g., Bloom et al. 2002; Garnavich et al. 2003). However, GRB 031211/SN 2002lt may be an exception ($z = 1.006$; Della Valle et al. 2003), since it has been suggested that it resembles the ordinary Type Ic SN 1994I (e.g., Baron et al. 1999) or the weak version of hypernova, SN 2002ap (e.g., Mazzali et al. 2002).

On the other hand, for studies on the late evolution of the OA of GRB 030329, it is also crucial to consider how the OA and SN components are separated, as shown by Lipkin et al. (2004).

In this paper, we update the spectra and LCs of SN 2003dh by applying the decomposition method of Mazzali et al. (2003) on all the observed spectra available to us. However, unlike Mazzali et al. (2003), who for simplicity removed as much blue flux as possible from the OT spectra, we also refer to the blue part of SN 1998bw spectra that begins to show the flux deficiency to determine the amount of OA subtraction. The bolometric LCs resulting from the two approaches are compared to one another and to model LCs.

2. SPECTRUM DECOMPOSITION

We studied 14 observed spectra published by Matheson et al. (2003), those taken with the MMT, Magellan, and Keck telescopes, spanning from April 1 to May 24 (see also Stanek et al. 2003b), and the May 8/9 and June 22 spectra taken with the Subaru telescope (Kawabata et al. 2003; Kosugi et al. 2004). The B-, V-, and R_C-band magnitudes that we derived from each Matheson et al. (2003) spectrum, except that of May 24, are consistent to within $\sim\pm0.15$ mag with the photometry of Lipkin et al. (2004) and with that reported in GCNs. The differences in colors are smaller, i.e., $\lesssim 0.1$ mag. The May 24 spectrum was of rather poor quality and was taken during the "Jitter Episode" when the OT varied rapidly by ~0.5 mag on a timescale of a few days (Stanek et al. 2003a; Matheson et al. 2003). It was fainter by ~1 mag in the R_C band than the above photometry, which had an almost daily coverage of the Jitter Episode. We recalibrated

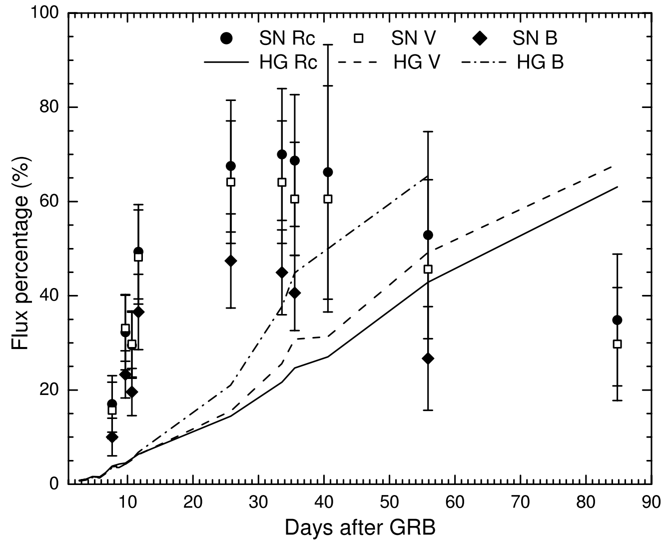

FIG. 1.—Contribution of the derived SN 2003dh spectrum in case I to the OT of GRB 030329 in the observer-frame R_C (*circles*), V (*squares*), and B (*diamonds*) bands, and that of the host galaxy template in these bands (*solid*, *dashed*, and *dash-dotted line*, respectively). Results shown are averaged over the cases of different OA spectrum templates. Error bars are estimated from statistical uncertainty and flux calibration uncertainty of the observed spectra and of the host galaxy.

its flux using $R_C = 21.4 \pm 0.15$ from the photometry. To compensate for similar flux discrepancies, the May and June Subaru spectra were calibrated to $R_C = 20.9 \pm 0.1$ and 21.8 ± 0.1, respectively, following Kawabata et al. (2003) and Kosugi et al. (2004).

All the spectra were converted to the rest frame of the GRB/SN ($z = 0.1685$), adopting a distance modulus of 39.54. We adopted the spectrum of NGC 3125, which was found by Kosugi et al. (2004) to show good coincidence to the observed narrow-line ratios, as the host-galaxy template, and calibrated its flux to $V = 22.7 \pm 0.3$ (Fruchter et al. 2003). This host-galaxy template was subtracted from the observations, whose flux contribution steadily increases from <10% in the first 20 days to ~40%–60% around 60 days (see Fig. 1), to derive the OT spectra. This operation, however, did not fully eliminate the narrow emissions, so the residuals, artifacts, and telluric lines were removed by hand.

We used each of the April 1, 2, 3, and 4 OT spectra as the OA template. The April 1, 2, and 3 spectra, after sufficient smoothing, can be well fitted using a power law $f_\lambda \propto \lambda^{-\beta}$, with $\beta = -1.06 \pm 0.00$, -1.12 ± 0.00, and -0.97 ± 0.00, respectively. The April 4 spectrum, however, shows significant deviations from a power law, which are not like SN features (see below). These fitting power laws and the smoothed April 4 spectrum were used in our actual spectrum subtraction.

As stated above, we scaled the OA template in flux and subtracted it from the OT spectrum to obtain the SN component, taking into account the fact that strong line blanketing should have greatly depressed the SN flux to the blue of ~3600 Å. Line blanketing (or blocking) describes the significant strengthening of UV/U continuum opacity caused by absorptions of numerous overlapping metal lines, mostly of Fe-group elements and Si, in a metal-rich, fast-moving SN atmosphere, such as that of a SN Ia (e.g., Pauldrach et al. 1996), or of a SN Ic (e.g., Baron et al. 1999), or of a hypernova (e.g., Mazzali et al. 2000).

We derived a quantitative criterion for the spectrum subtraction from the spectra of SN 1998bw (Patat et al. 2001), which have good U-band coverage. In the SN 1998bw spectra, the flux

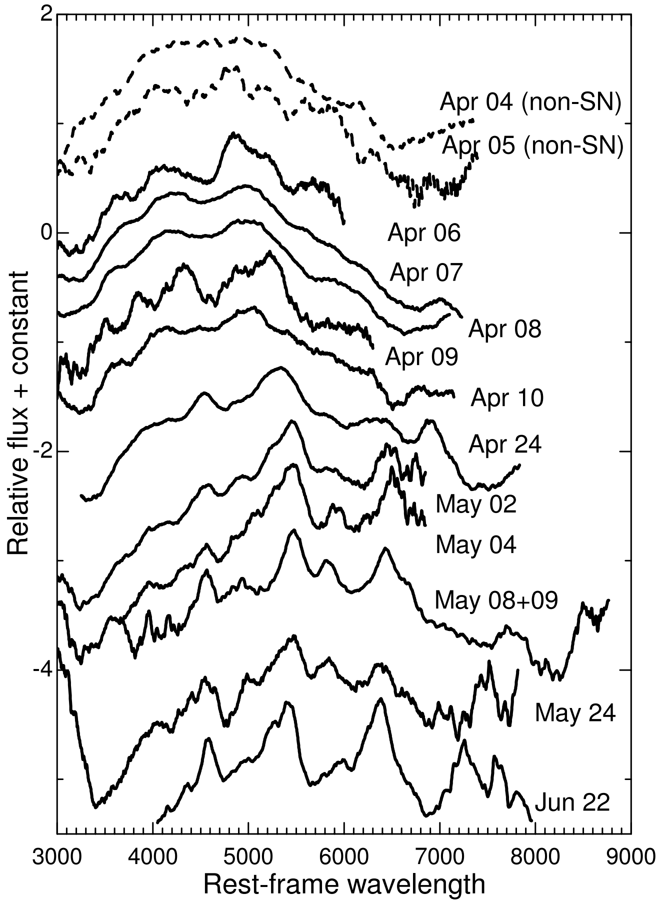

FIG. 2.—Evolution of the derived spectra (*solid lines*) in case I from April 4 to June 22. The spectra are obtained by subtracting the April 3 OA template (except for April 4 and 7, see text) and the host galaxy template from the OT spectra (Stanek et al. 2003b; Kawabata et al. 2003; Matheson et al. 2003; Kosugi et al. 2004). Spectra shown are smoothed for clarity. Those on April 4 and 5 (*dashed lines*) are not SN-like, displaying no convincing SN features.

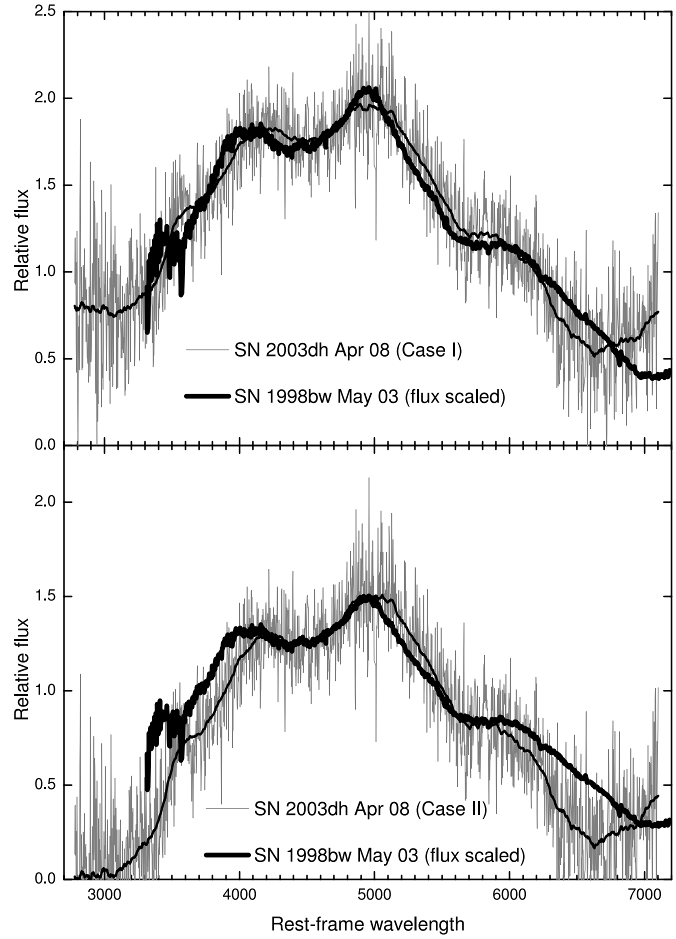

FIG. 3.—Comparison of the derived April 8 SN 2003dh spectrum (*thin gray line*: nonsmoothed; *thin black line*: smoothed) in case I (*top*) and case II (*bottom*) with an early-time SN 1998bw spectrum (*thick black line*; Patat et al. 2001).

drops rapidly from $\sim$4000 to $\sim$3600 Å, along the Ca II H and K line profile, to reach the flux-deficiency range. The flux ratio of two reference wavelengths, f_{4000}/f_{3350}, evolves from $\sim$2 in the first 15 days to $\sim$3 between 15 and 40 days, and to $\sim$4 in the rest of the photospheric epoch. We imposed these values on the derived SN 2003dh spectra (case I). On the other hand, we also tried the simple treatment of Mazzali et al. (2003), forcing the minimal SN spectral flux in the *U*-band to zero (case II). Since the OT spectra were noisy, in order to apply these criteria, we smoothed them before subtraction by averaging every 100 or 75 wavelengths points.

To determine the OA flux for epochs of the Subaru spectra that have insufficient blue coverage, we fitted the OA flux evolution derived from decomposing the earlier spectra with a power law $f \propto t^{-\alpha}$. The best-fit power-law index is about 2.75 ± 0.15 for case I and about 2.40 ± 0.15 for case II.

We show in Figure 2 the spectra of SN 2003dh between April 6 and June 22 that we derived from the smoothed OT spectra in case I by subtracting the April 3 OA template, except for April 7. Using the different OA templates mentioned above did not change the overall spectral appearance in most cases and affects the continuum shape, and hence the multiband photometry, only slightly. However, for April 7, if any of the above OA templates were used, the derived spectrum turned out to be too blue to look like one of any Type Ic SN or hypernova. We assumed an OA spectrum of $f_\lambda \propto \lambda^{-1.5}$ to get the "reasonable" April 7 SN spectrum shown in Figure 2. The above problem of the April 7 spectrum was likely caused by observational uncertainties, because the difference between $B - R_C$ of this OA spectrum and that of the April 3 spectrum, i.e., $\sim$0.23, is the same as that between the observed April 7 spectrum and the Lipkin et al. (2004) photometry.

The resulting SN spectra in case II are similar to those of case I, but they are fainter and redder, since more OA flux was subtracted, especially in the *UB* bands. To exemplify the difference between these two cases, in Figure 3 we compare the derived April 8 SN spectra with the SN 1998bw spectrum at a similar epoch. The SN spectrum in case I matches both the red and blue parts of the SN 1998bw spectrum well, while that in case II shows a significant blue excess relative to the latter. The difference becomes small for the spectra of May and later, when the OA has greatly faded and contributes about 10%–15% of the total flux or less (see Fig. 1).

The April SN spectra resemble those of SN 1998bw at similar epochs, as discovered by Stanek et al. (2003b), Hjorth et al. (2003), and Matheson et al. (2003). On the other hand, Kawabata et al. (2003) and Kosugi et al. (2004) pointed out that the red part of the May and June Subaru spectra resembles the SN 1997ef spectra, where the O I λ7774 and Ca II IR triplet lines are well separated, more than they do the SN 1998bw spectra, where these two lines still strongly blend at such epochs (see also Mazzali et al. 2003). This seems to be confirmed by the May 24 spectrum of Matheson et al. (2003), as shown in Figure 4, where we compare the derived SN spectrum with those of SN 1997ef

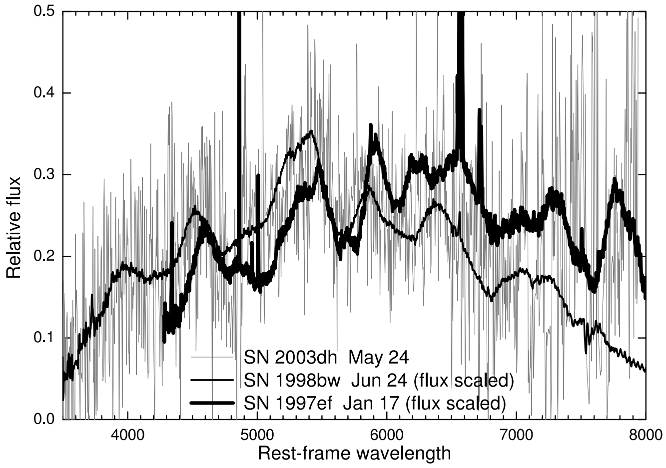

Fig. 4.—Comparison of the derived May 24 SN 2003dh spectrum (*thin gray line*) in case I with the spectra of SN 1998bw (*thin black line*; Patat et al. 2001) and SN 1997ef (*thick black line*; Matheson et al. 2001) at similar epochs.

and SN 1998bw at similar epochs. Although the spectrum is noisy, it seems to show separate O I $\lambda7774$ and Ca II IR triplet lines, similar to SN 1997ef and unlike SN 1998bw (see Fig. 2 for a smoothed spectrum), if the red end has not been much polluted by the second-order spectrum.

We cannot find convincing SN features in the derived spectra on April 4 and 5, which are also shown in Figure 2 for comparison. (The April 4 spectrum shown was obtained using the April 2 OA template.) First of all, they only contribute a few percent to the total flux, which is within the flux calibration error in the observations (K. Z. Stanek & T. Matheson 2004, private communication; see also Matheson et al. 2003). In addition, the derived April 4 spectrum is continuum-like, similar to the derived April 3 spectrum in Hjorth et al. (2003), while the hypernova SN 2002ap at ~2–4 days already displays clear, broad line features (Mazzali et al. 2002; Kinugasa et al. 2002). Furthermore, even if the dubious "broad features" in the derived April 5 spectrum are real, they do not match the SN features on April 6 and later, and hence are unlikely to be related to the SN. So we confirm that the April 3–5 OT "color event" (Matheson et al. 2003), corresponding to the LC "bump D" of Lipkin et al. (2004) and close to the supposed jet break, is not of SN origin.

3. LIGHT CURVES

We assembled the rest-frame $UBVR_CI_C$ multicolor LCs for SN 2003dh from broadband spectroscopy of the derived SN spectra, excluding April 7 (see above), and corrected for the Galactic reddening of $E(B-V)=0.025$ (Schlegel et al. 1998). The LCs in both case I and II are shown in Figure 5 and compared with those of SN 1998bw [$z=0.0085$, $\mu=32.89$, and $A(V)=0.2$; Galama et al. 1998; Patat et al. 2001]. These are the results averaged over the cases of different OA templates. We list in Table 1 the LC data in case I and their error bars, which vary between ±0.2 and ±0.4 mag. We estimated the error bars from statistical uncertainty; flux calibration uncertainty of the observed spectra, i.e., ±0.15 mag for the Matheson spectra and ±0.1 mag for the Subaru spectra; and flux calibration uncertainty of the host galaxy, i.e., ±0.3 mag. They are not shown in Figure 5, for clarity.

The derived SN 2003dh LCs are more similar to those of SN 1998bw than to those of any other known hypernova or Type Ic SN, but on the other hand, they are also narrower than those of SN 1998bw in both case I and II. The case I LCs are as bright as SN 1998bw before maximum but fainter by about 0.3–0.6 mag

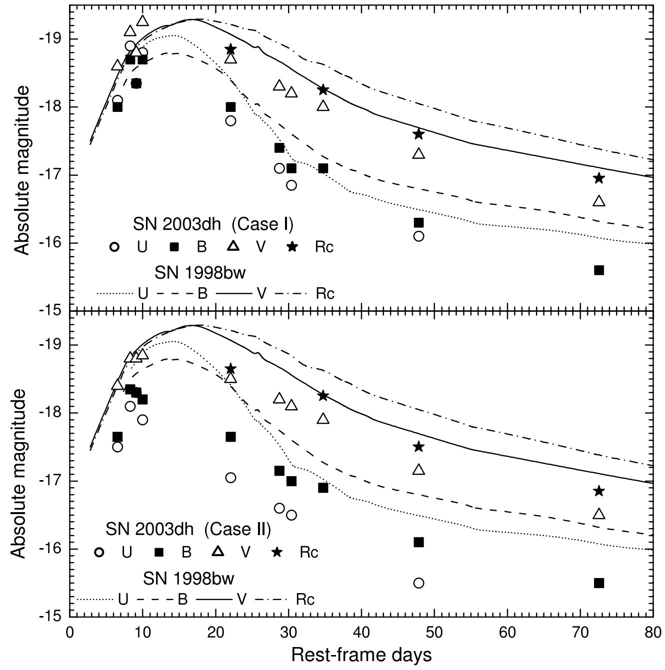

Fig. 5.—Comparison of our rest-frame U (*circles*), B (*squares*), V (*triangles*), and R_C (*stars*) LCs of SN 2003dh in case I (*top*) and case II (*bottom*) with those of SN 1998bw (*dotted*, *dashed*, *solid*, and *dash-dotted line*, respectively; Galama et al. 1998). Results shown are averaged over the cases of different OA templates.

after maximum. Those in case II are even fainter, particularly in the U and B bands. We think that case II has underestimated the UB flux to some extent, by comparison with SN 1998bw and other hypernovae and Type Ic SNe. Case I seems therefore more realistic.

Our case I results are consistent with the apparent V-band LC derived by Hjorth et al. (2003) through decomposing the VLT spectra of the first month. Their best-fit OA spectrum, $f_\lambda \propto \lambda^{-0.8}$, is not as steep as our templates, however. For comparison, we calculated the apparent V magnitudes of our case I SN spectra converted to the observer frame. Their magnitudes on rest-frame day 28, 20, and 8 are only fainter than ours by $\lesssim0.1$ mag, while their day 10 is ~0.2 mag brighter. The differences are within our respective error bars. Hjorth et al. (2003) also showed a day 4 magnitude much brighter than SN 1998bw. However, the corresponding spectrum is not SN-like. As argued by Matheson et al. (2003) and confirmed by us, SN features did not emerge until April 6. It would be useful to apply the same treatment to the VLT spectra. For example, the LC around maximum could be defined much better using the VLT spectrum on rest-frame day 16.

The real SN LC inferred from the spectrum decomposition of Matheson et al. (2003) may also be narrower than that of SN 1998bw, similar to our results, although it was stated by those authors that the two SNe closely resemble each other. They were able to model the observed R_C-band LC by combining the derived OA R_C-band LC and a V-band LC of SN 1998bw, corrected for time dilation. However, as pointed out by Lipkin et al. (2004), they would have suggested a SN LC ~0.4–0.6 mag fainter than SN 1998bw if K-corrections had been taken into account. K-corrections for SN 1998bw have been calculated for various redshifts (J. Deng 2005, in preparation). The one of interest here, $R_C(z=0.1685)-V(z=0.0085)$, varies slightly between -0.29 and -0.34 in the first 100 days. The redshifted and K-corrected V-band LC of SN 1998bw exceeds the observed R_C-band brightness of the GRB/SN at some epochs of the Jitter Episode (~day 50–70), confirming the findings of Lipkin et al.

TABLE 1
SN 2003dh LCs from Spectrum Decomposition (Case I)

Days[a]	$M(U)$[b]	$M(B)$[b]	$M(V)$[b]	$M(R_C)$[b]	BC(U)[c]	BC(B)[c]	BC(V)[c]	BC(R_C)[c]	M(bol)[d]
5.7	-18.50 ± 0.40	-18.40 ± 0.40	-19.05 ± 0.35	...	0.00	−0.05	0.30	0.25	-18.60 ± 0.40
6.6	-18.10 ± 0.35	-18.00 ± 0.35	-18.60 ± 0.30	...	0.05	−0.05	0.35	0.25	-18.15 ± 0.35
8.3	-18.90 ± 0.25	-18.70 ± 0.25	-19.10 ± 0.30	...	0.15	0.00	0.35	0.30	-18.75 ± 0.30
9.1	-18.35 ± 0.25	-18.35 ± 0.25	-18.80 ± 0.20	...	0.20	0.00	0.35	0.30	-18.40 ± 0.25
10.0	-18.80 ± 0.20	-18.70 ± 0.20	-19.25 ± 0.20	...	0.20	0.00	0.35	0.30	-18.80 ± 0.25
22.1	-17.80 ± 0.20	-18.00 ± 0.20	-18.70 ± 0.20	-18.85 ± 0.20	−0.30	−0.30	0.35	0.50	-18.35 ± 0.20
28.7	-17.10 ± 0.20	-17.40 ± 0.20	-18.30 ± 0.20	...	−0.80	−0.60	0.35	0.60	-18.00 ± 0.20
30.4	-16.85 ± 0.20	-17.10 ± 0.20	-18.20 ± 0.20	...	−0.95	−0.60	0.35	0.60	-17.75 ± 0.20
34.7	...	-17.10 ± 0.35	-18.00 ± 0.35	-18.25 ± 0.35	−0.95	−0.70	0.30	0.65	-17.70 ± 0.35
47.8	-16.10 ± 0.35	-16.30 ± 0.35	-17.30 ± 0.35	-17.60 ± 0.35	−0.95	−0.65	0.25	0.60	-17.00 ± 0.35
72.6	...	-15.60 ± 0.35	-16.60 ± 0.35	-16.95 ± 0.35	−0.70	−0.50	0.30	0.60	-16.25 ± 0.40

Note.—All magnitude data and error bars are accurate to 0.05 mag.
[a] Days in the rest frame ($z = 0.1685$) since GRB 030329 on 2003 March 29.48 UT.
[b] Absolute magnitudes of derived SN spectra [$z = 0.1685$, $\mu = 39.54$, and $E(B-V) = 0.025$].
[c] Bolometric corrections of SN 1998bw calculated based on Galama et al. (1998) and Patat et al. (2001).
[d] Average *UVOIR* bolometric magnitudes adopting the B-, V-, and R_C-band BCs of SN 1998bw.

(2004). On the other hand, upon close inspection, the combined LC shown in Figure 13 of Matheson et al. (2003) seems to underestimate the observations at the early epochs, i.e., before SN maximum.

The SN LCs recommended by Lipkin et al. (2004), i.e., those of SN 1998bw stretched by 0.8 times and attenuated by 0.3 mag, are ~0.05–0.55 mag fainter, in the rest frame, than our case I results, depending on the individual epochs and the bands. Our B- and U-band LCs also decline faster after day 30 than the Lipkin LCs in both case I and case II. Only the V- and R_C-band LCs in case II seem to match the Lipkin ones. Lipkin et al. (2004) argued that the $\Delta m = 0.3$ mag is the lower limit on their attenuation to meet the brightness minimum in the Jitter Episode. Our results obviously also meet that requirement.

We built the *UVOIR* bolometric LCs for SN 2003dh, using the above multicolor LCs in order to compare with theoretical models. However, we did not follow the common practice in which a spectral energy distribution (SED) was constructed and integrated, because of the lack of the rest frame I_C-band LC and near-IR data. Instead, we calculated the bolometric corrections (BCs) of SN 1998bw in each band and applied them to the SN 2003dh multicolor LCs (see Table 1). This is justified by the overall spectral similarity of these two SNe. The R_C-band BC of SN 1997ef seems more suitable for May and June, because the spectra in this period are more similar in the red part to SN 1997ef than to 1998bw. We derived the R_C-band BC in such epochs from the SN 1997ef spectra (Mazzali et al. 2000) but found that its value, ~0.5–0.6, is similar to that of SN 1998bw, ~0.6. Therefore, we ignored the difference between them.

We averaged the bolometric LCs converted from the individual LC of each band to make up for the color difference between SN 2003dh and SN 1998bw. The average was taken over the B and V bands for most epochs or over the B, V, and R_C bands, if the last was available. We excluded the U-band to avoid potentially large uncertainties. The bolometric LC converted from the U-band LC is more or less consistent with the average one in case I, but in case II it is ~0.4–0.5 mag fainter than the average one. In many cases, the U band contributes to only a small fraction of the total flux of Type Ic SNe, owing to line blanketing, so the bolometric LC may not be well correlated with the U-band LC. Moreover, the BCs of SN 1998bw in the U band may not be as reliable as in the other bands, because of the common difficulties related to U-band photometry. In contrast, the bolometric LCs converted from the B-, V-, and R_C-band LCs agree with the average one within ~±0.15 mag in both case I and case II.

We show our average bolometric LCs of both case I and case II in Figure 6 (*top*), where SN 2003dh is compared with the hypernovae SN 1998bw (Patat et al. 2001), SN 1997ef (Mazzali et al. 2000), and SN 2002ap (Mazzali et al. 2002; Yoshii et al. 2003) and normal Type Ic SN 1994I (B. P. Schmidt & R. P. Kirshner 1993, private communication; Nomoto et al. 1994; Richmond et al. 1996). Although as bright as SN 1998bw before maximum, SN 2003dh was significantly fainter after maximum, resulting in relatively narrow LCs. In case I, the brightness discrepancy

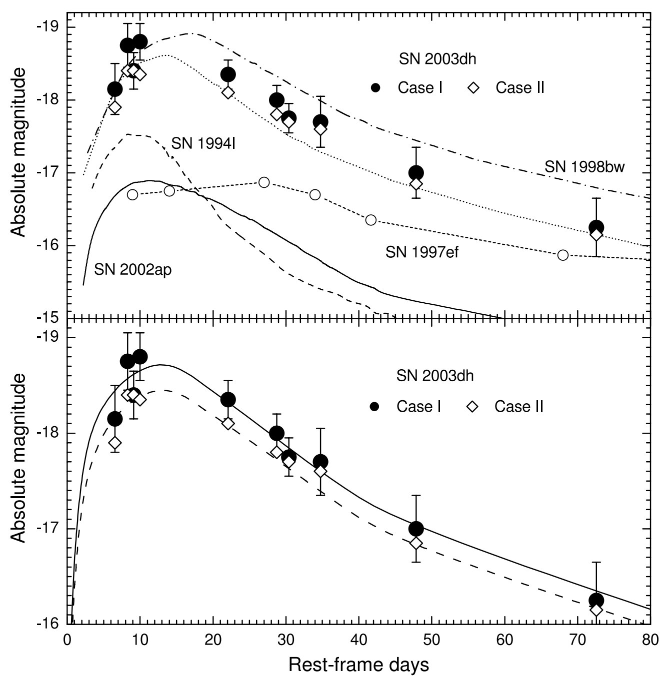

Fig. 6.—*Top*: Comparison of our bolometric LCs of SN 2003dh in case I (*filled circles*) and case II (*diamonds*) with that suggested by Lipkin et al. (2004; *dotted line*) and those of (see text for references) SN 1998bw (*dash-dotted line*), SN 1997ef (*open circles with short-dashed line*), SN 2002ap (*solid line*), and SN 1994I (*dashed line*). Error bars in case II are not shown for clarity. *Bottom*: Comparison of our bolometric LCs of SN 2003dh with model LCs (*solid line*: 7 $M_\odot$, 3.5×10^{52} ergs, and 0.4 $M_\odot$ ^{56}Ni; *dashed line*: 8 $M_\odot$, 4×10^{52} ergs, and 0.35 $M_\odot$ ^{56}Ni).

increases from $\sim$0.35 mag around rest-frame day 20 to $\sim$0.55 mag around day 70, while in case II it is mostly $\sim$0.5–0.6 mag after maximum. The LC decline is about 1.4 times faster than SN 1998bw in case I, confirming the result of Hjorth et al. (2003). The case II LC resembles the solution suggested by Lipkin et al. (2004), i.e., that the LC of SN 2003dh is similar to that of SN 1998bw stretched by 0.8 times and attenuated by 0.3 mag. On the other hand, the above differences notwithstanding, SN 2003dh is still much more similar to SN 1998bw than to the other SNe shown in the figure with regard to the bolometric LC.

We suggest that the peak brightness of SN 2003dh is lower than that of SN 1998bw, even though our LCs do not capture the exact time of peak, which lies between rest-frame day 10 and 15, according to Hjorth et al. (2003). For case II this can easily be seen in Figure 6. However, in case I, our April 8 and 10 magnitude points lie above the bolometric LC of SN 1998bw and could lead to a peak almost as bright as SN 1998bw. On the other hand, the corresponding spectra at these epochs in Figure 2 display SN features not as prominent as on April 6 and 9. So it is possible that there is still some residual OA continuum, whose spectrum would not be a power law. The actual SN LC may pass between the bright April 8 and 10 points and the faint April 6 and 9 points, leading to a somewhat fainter peak than SN 1998bw.

We modeled the bolometric LCs starting from the ejecta model COMDH constructed in Mazzali et al. (2003). We modified its mass M_{ej}, kinetic energy E_K, and ejected ^{56}Ni mass $M(^{56}\mathrm{Ni})$, while keeping the ratio E_K/M_{ej} constant. COMDH is a one-dimensional spherical density structure against velocity that was derived from theoretically synthesizing the SN spectra of April 10, 24, and May 8/9. It has $M_{ej} \sim 8\ M_\odot$, $E_K \sim 4 \times 10^{52}$ ergs, and a ^{56}Ni mass of 0.35 $M_\odot$. The density structure above 25,000 km s^{-1} mimics the hypernova model of SN 1998bw (Nakamura et al. 2001) to reproduce the SN 1998bw-like early-time spectra and very broad lines, while below 15,000 km s^{-1} it is adjusted so as to follow the spectral evolution into the SN 1997ef-like later epoch. Our derived SN spectra are similar to those studied by Mazzali et al. (2003), as far as spectral features are concerned, and the small differences in the total flux are not expected to modify the main results of spectral modelling obtained in that paper. Therefore, we did not model the spectra again, but rather we fixed E_K/M_{ej} at the original COMDH value, i.e., $\sim$5, because this ratio, which characterizes the line widths and the strength of line blending, is the key parameter in spectrum modeling.

We used the same one-dimensional SN radiation hydrodynamical and gamma-ray transfer codes (Iwamoto et al. 2000) used in Mazzali et al. (2003), but we adopted the treatment of the Eddington factor proposed by Gómez-Gomar & Isern (1996), instead of the simple Eddington approximation, and we approximated the Rosseland mean opacity using an empirical relation to the electron-scattering opacity derived from the TOPS database (Magee et al. 1995), rather than assuming a constant line opacity. Isotope ^{56}Ni was assumed to be homogeneously mixed throughout the ejecta, in order to reproduce the rapid brightening before maximum, as in other hypernovae, such as SN 1998bw (Nakamura et al. 2001), SN 1997ef (Iwamoto et al. 2000), and SN 2002ap (Mazzali et al. 2002). Since COMDH is not the result of an explosion simulation, the other composition was assumed to be 90% O and 10% Si. Our synthetic LC of the original COMDH is consistent with that of Mazzali et al. (2003).

Our bolometric LC in case I is best fitted with the slightly reduced values $M_{ej} \sim 7\ M_\odot$, $E_K \sim 3.5 \times 10^{52}$ ergs, and $M(^{56}\mathrm{Ni}) \sim 0.4\ M_\odot$, while that in case II can be well reproduced using the original COMDH. The best-fitting model LCs are shown in Figure 6 (*bottom*).

The fitting model parameters for our preferred case I can be relaxed to $M_{ej} \sim 7 \pm 3\ M_\odot$ and $E_K \sim 3.5 \pm 1.5 \times 10^{52}$ ergs, with $E_K/M_{ej} \sim 5$, if the error bars shown in Figure 6 are taken into consideration. To derive the upper and lower limits, we assumed that we had either under- or overestimated the SN flux throughout the postmaximum epochs. We did not place much weight on fitting the premaximum LC, because it is not well defined, and because the model LC in that phase is more sensitive to the ^{56}Ni distribution. Finally, we constrained the most likely range for the ^{56}Ni mass to $M(^{56}\mathrm{Ni}) \sim 0.4^{+0.15}_{-0.1}\ M_\odot$.

4. DISCUSSION

We discussed an optimal OA subtraction method to separate the SN spectra from the OA of GRB 030329 and to construct the *UVOIR* bolometric LC of SN 2003dh. The LC is narrower than that of SN 1998bw, rising as fast before maximum but reaching a somewhat fainter maximum and declining about 1.2–1.4 times faster afterward. Our spherical LC model parameters, $M_{ej} \sim 7 \pm 3\ M_\odot$ and $E_K \sim 3.5 \pm 1.5 \times 10^{52}$ ergs ($E_K/M_{ej} \sim 5$), allowing for LC uncertainties, are lower than SN 1998bw, which is another GRB-associated hypernova and has been modeled with $M_{ej} \sim 10\ M_\odot$ and $E_K \sim 4 - 5 \times 10^{52}$ ergs (Nakamura et al. 2001; Maeda et al. 2003). SN 1997ef, a hypernova displaying no GRB, as well as its replica SN 1997dq (Mazzali et al. 2004), is as massive as SN 1998bw and SN 2003dh but less energetic ($E_K \sim 1 - 2 \times 10^{52}$ ergs; Iwamoto et al. 2000; Mazzali et al. 2000).

We suggest that SN 2003dh/GRB 030329 is the explosion of an $\sim$6–14 $M_\odot$ C+O star, assuming a central remnant of $\sim$2–4 $M_\odot$, which may evolve from an $\sim$25–40 $M_\odot$ main-sequence star (Nomoto & Hashimoto 1988) losing its H and He envelopes through stellar winds or binary accretion (Nomoto et al. 1995). The upper limit is comparable to the values used for SN 1998bw, and the lower limit is well above that for SN 2002ap (Mazzali et al. 2002), a marginal hypernova without an associated GRB. The parameter range could be further narrowed by spectral modeling, as done in Mazzali et al. (2003). However, the result in that paper could be updated if the spectra presented here, which are a little brighter and extend to later epochs, are modeled, although the characteristic parameter E_K/M_{ej} is expected to have a similar value.

The model parameters will probably be modified when asymmetry is considered, as was the case for SN 1998bw (Höflich et al. 1999; Maeda et al. 2002). The changes in M_{ej} and ^{56}Ni mass are not expected to be large, while E_K can be significantly reduced in an asymmetric model, depending on the geometry. In the case of SN 1998bw, Maeda et al. (2002) found an axial ratio of about 3:2 and a viewing angle of about 15° from the pole, by modeling the late-time spectra. Their best-fitting E_K is $\sim 10^{52}$ ergs, i.e., one-fourth that in the spherical model of Nakamura et al. (2001). The SN 2003dh asymmetry is probably similar. This is modest compared to the GRB. Kawabata et al. (2003) detected marginal polarization (<1%) in 2003 May and suggested that it was mostly of local interstellar origin. Greiner et al. (2003) reported an OT polarization level of $\sim$0.5%–2% at times between $\sim$10 and 40 days after the GRB and assumed that interstellar polarization was negligible. This polarization level seems consistent with other envelope-stripped core-collapse SNe (e.g., Wang et al. 2001; Leonard et al. 2002) and may suggest an asphericity of $\sim$15%–30% (Höflich 1991).

The evolution of the OA flux after April 3–5 derived from our case I spectrum decomposition can be fitted using a power-law

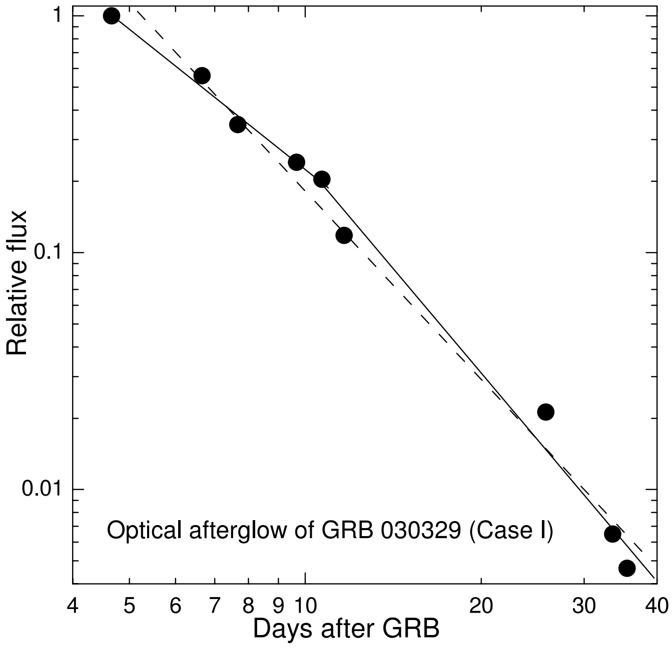

FIG. 7.—Comparison of the OA LC of GRB 030329 after April 3 (*circles*) with best-fitting single power law (*dashed line*: $f \propto t^{-2.6\pm0.1}$) and broken power law (*solid line*: $t \lesssim 10$ days, $f \propto t^{-2.0\pm0.1}$; $t \gtrsim 10$ days, $f \propto t^{-2.9\pm0.2}$). The LC is derived from our spectrum decomposition in case I using the April 3 OA spectrum template, and the flux shown is normalized relative to the template.

decay with an index of $\alpha \sim 2.7$ (see Fig. 7 for an example). This is steeper than what was suggested by Lipkin et al. (2004), i.e., $\alpha \sim 2.0$ after the jet break that occurred around day 3–8. On the other hand, we can also fit our results using a broken power law, i.e., $\alpha \sim 2.0$ before ~day 10–11 and $\alpha \sim 2.9$ after that, in view of the two-jet model of Berger et al. (2003), who invoked a second, wide jet to explain radio observations and suggested that its break took place around day 10. However, the above indices are statistically rough due to the small number of data points, and we cannot tell which fitting is better.

We have corrected for the Galactic extinction only. Matheson et al. (2003) derived a local reddening of $E(B-V) \sim 0.03$–0.09 from the Balmer decrement of the host galaxy. However, the assumption of Case B recombination underlying this estimate may not be correct. Moreover, their early OT SED constructed from optical-IR photometry is consistent with the case of no local extinction. The negligible local interstellar polarization (<0.3%) argued by Greiner et al. (2003) corresponds to a negligible local $E(B-V) < 0.03$ mag (Serkowski et al. 1975), while the values discussed by Kawabata et al. (2003) may suggest a local $E(B-V) < 0.06$–0.1 mag. Bloom et al. (2004) obtained an upper limit for the local extinction, i.e., $A(V) < 0.3$ mag, from their early optical-IR photometry, although they adopted this upper limit as the real local extinction value and applied it to their SN LC. Šimon et al. (2004) also argued for $E(B-V) < 0.1$ mag, comparing the colors of the OA with a group of 25 OAs.

It is interesting that the three SNe with the most convincing GRB connections, i.e., SN 1998bw, SN 2003dh, and SN 2003lw, happen to have relatively similar spectra and LCs, considering the large differences between their respective GRBs and the general heterogeneity among hypernovae and among Type Ic SNe. Studies of SN 2003lw revealed SN 1998bw-like spectra and LCs that are probably ~0.3–0.7 mag brighter and ~1.1–1.2 times broader than SN 1998bw (Malesani et al. 2004; P. A. Mazzali 2005, in preparation), suggesting a somewhat more massive star. GRB 980425 and GRB 031203 were both extremely weak gamma-ray events, $E_\gamma^{\rm iso}$ being $\sim 8 \times 10^{47}$ ergs for GRB 980425 (Galama et al. 1998) and $\lesssim 10^{50}$ ergs for GRB 031203 (Sazonov et al. 2004), and their respective OA was not detected or was detected only marginally (Malesani et al. 2004). In contrast, $E_\gamma^{\rm iso}$ of GRB 030329 is as high as $\sim 1 \times 10^{52}$ ergs (Price et al. 2003), and its OA dominated the early optical observations, although the beaming-corrected gamma-ray energy, $\sim 5 \times 10^{49}$ ergs, is still significantly lower than the bulk of normal GRBs (Berger et al. 2003).

Does this imply any correlation between the progenitor mass, the SN kinetic energy, and the GRB/OA intensity? On the one hand, it is possible that a more massive star causes the deposition of more energy near the central explosion engine, e.g., the initial jet. On the other hand, one may speculate that the GRB/OA jet has dissipated more energy to the SN ejecta after penetrating the more massive star, and meanwhile, may also have given out more energy to some less relativistic jet component, such as the wide radio component proposed by Berger et al. (2003). Note that the bulk of the explosion energy for all three events lies in the SN kinetic energy E_K, not in the GRB and its afterglow. Thus, a small relative change in E_K, e.g., a positive one, can accompany a big change in the GRB energy, positive or not. A positive correlation between E_K and SN ejecta mass can help prevent big differences in the SN spectra, characterized by $E_K/M_{\rm ej}$, and LCs, which have a typical timescale of $\sim M_{\rm ej}^{3/4}/E_K^{1/4}$ (Arnett 1982). The possibility of significantly different viewing angles for the three GRBs seems to be disfavored by the spectral similarity of the related SNe, unless the SN asphericity is small. Ramirez-Ruiz et al. (2004) suggest that at least GRB 030329 and GRB 031203 are compatible with the premise that they are the same event viewed very close to the jet axis and a few degrees away from it, respectively. The viewing angle of GRB 980425 was determined by Maeda et al. (2002) to be ~15°, on the basis of the nebular line profiles and of aspherical explosion models. This may require an intrinsically weaker GRB.

More examples of GRB-SN connections are required to clarify this problem. Della Valle et al. (2003) argued that the SN 2002lt hosted in GRB 021211 is similar to the normal Type Ic SN 1994I. However, the available rest-frame U-band photometry does not exclude a SN LC as bright and as broad as SN 1998bw. In the case of GRB 011121, Garnavich et al. (2003) detected a LC "bump" in the OT. Based on photometry, they argued for a very blue SN (named SN 2001ke), different from SN 1998bw both in colors and in temporal evolution. The only available spectrum is unfortunately too noisy to show obvious SN features.

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