THE TYPE Ic HYPERNOVA SN 2003dh/GRB 030329

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ABSTRACT

The spectra of SN 2003dh, identified in the afterglow of GRB 030329, are modeled using radiation transport codes. It is shown that SN 2003dh had a high explosion kinetic energy ($\sim 4 \times 10^{52}$ ergs in spherical symmetry), making it one of the most powerful hypernovae observed so far and supporting the case for association between hypernovae and gamma-ray bursts. However, the light curve derived from fitting the spectra suggests that SN 2003dh was not as bright as SN 1998bw, ejecting only $\sim 0.35\ M_\odot$ of ^{56}Ni. The spectra of SN 2003dh resemble those of SN 1998bw around maximum, but later they look more like those of the less energetic hypernova SN 1997ef. The spectra and the inferred light curve can be modeled adopting a density distribution similar to that used for SN 1998bw at $v > 25{,}000$ km s^{-1} but more like that of SN 1997ef at lower velocities. The mass of the ejecta is $\sim 8\ M_\odot$, somewhat less than in the other two hypernovae. The progenitor must have been a massive star ($M \sim 35$–$40\ M_\odot$), as for other hypernovae. The need to combine different one-dimensional explosion models strongly indicates that SN 2003dh was an asymmetric explosion.

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

1. INTRODUCTION

Evidence that at least some gamma-ray bursts (GRBs) are connected to supernovae (SNe) is mounting. After the serendipitous discovery of SN 1998bw in coincidence with GRB 980425 (Galama et al. 1998), several other cases of possible SNe in GRBs have been reported (e.g., Bloom et al. 2002; Garnavich et al. 2003). All of these were, however, based only on the detection of "bumps" in the GRB afterglows' (AGs) light curves, which could be decomposed to look like the light curve of SN 1998bw.

SN 1998bw was no ordinary SN. Its broad spectral features were explained as indicating a very energetic Type Ic SN (arising from the collapse of the bare CO core of a massive star). Because of its high explosion kinetic energy ($\sim 5 \times 10^{52}$ ergs in spherical symmetry), and the consequently very broad spectral lines, SN 1998bw was called a "hypernova" (Iwamoto et al. 1998). Other hypernovae have been discovered and analyzed (e.g., SNe 1997ef [Iwamoto et al. 2000; Mazzali, Iwamoto, & Nomoto 2000] and SN 2002ap [Mazzali et al. 2002]), but none were associated with a GRB. This may be related to the fact that none of these SNe were either as bright or as powerful as SN 1998bw. So far, the only other positive detection of a SN spectrum in a GRB AG is the case of GRB 021211/SN 2002lt (Della Valle et al. 2003).

Given this intriguing but insufficient evidence, excitement mounted when a very nearby GRB was detected (GRB 030329, $z = 0.1685$; Greiner et al. 2003), as a possible SN may be relatively easily observable in the light of the AG. Indeed, broad features characteristic of a SN spectrum were reported by Stanek et al. (2003) and later by Hjorth et al. (2003). The SN (SN 2003dh) appeared to be similar to SN 1998bw. However, spectra at ~ 1 month had changed somewhat, looking more like those of the less energetic hypernova SN 1997ef (Kawabata et al. 2003).

There are significant differences between the SN 2003dh light curves of Matheson et al. (2003) and Hjorth et al. (2003). These may be due to the different observational methods and to major difficulties with subtraction of (1) the underlying AG spectrum, which can change with time in an unknown way, and (2) the host galaxy background. In particular, the Hjorth et al. (2003) light curve rises much more rapidly, reaches a brighter peak, and then drops much faster. The Matheson et al. (2003) light curve, on the other hand, has a slower rise and resembles that of SN 1998bw. Unfortunately, neither light curve covers the likely time of peak, ~ 12–15 days after the GRB, because this time coincided with full Moon. The peak rest-frame M_V may have been between -18.5 and -19.1, depending on the data set used and the estimated extinction. Bloom et al. (2003), however, find that SN 2003dh may have been as bright as $M_V = -19.8 \pm 0.4$ at peak. They used an extinction $A_V \approx 0.4$ toward SN 2003dh, explaining at least part of the discrepancy, assumed a SN 1998bw–like light curve, and did not use spectral information in decomposing the light curve.

2. SPECTRAL MODELS

Light-curve models alone cannot uniquely constrain the properties of a SN, as models yielding similar light curves may give rise to different synthetic spectra (e.g., Iwamoto et al. 1998). Fitting both light curves and spectra is a much more effective approach.

Unfortunately, in the case of SN 2003dh the exact shape of the light curve is not yet certain. Therefore, we derived fiducial SN spectra by rescaling the early power-law spectrum of the AG to the blue flux of the later spectra, where a SN signature was evident, and subtracting it off. Attributing the entire blue

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TABLE 1
MODELS

Model	$M_{ej}/M_{\odot}$	E_{51}	$M(^{56}Ni)$[a]
CO100E18[b]	9.6	18	0.32
CO138E50[c]	10.4	50	0.32
COMDH	8.0	38	0.35

[a] Values required to reproduce the brightness of SN 2003dh.
[b] From Mazzali et al. 2000.
[c] From Nakamura et al. 2001.

flux to the AG is justified by the fact that because of line-blanketing Type Ib/c SNe, like SNe Ia, always show a flux deficiency to the blue of ~3600 Å (e.g., Mazzali et al. 2002). At the third epoch, the blue continuum indicative of the AG is very weak, and no subtraction was applied. We fitted three spectra of SN 2003dh using our Monte Carlo code (Mazzali & Lucy 1993; Lucy 1999; Mazzali 2000).

The first spectrum was obtained at the MMT on 2003 April 10 (Matheson et al. 2003). This is ~12 days after the GRB, i.e., ~10 rest-frame days into the life of the SN, assuming that the SN and the GRB coincided in time. The spectrum is characterized by very broad absorption lines, and it is similar to those of SN 1998bw at comparable epochs. Using the same explosion model as for SN 1998bw (model CO138E50; Nakamura et al. 2001; Table 1), a good match can be obtained for $\log L = 42.83$ and $v(ph) = 28,000$ km s^{-1} (Fig. 1). The synthetic spectrum has $V = -18.53$, $M(Bol) = -18.37$. While the luminosity is lower than in SN 1998bw, the photospheric velocity is comparable [for SN 1998bw, we had $v(ph) = 31,600$ km s^{-1} on day 8 and 20,700 on day 16]. This suggests that SN 2003dh ejected a significant amount of high-velocity material in our direction, which is understandable since we observed the GRB. SN 1998bw may have been even more energetic, but is was probably viewed less on-axis since its associated GRB was much weaker than GRB 030329. Note that we cannot confirm the claim that SN 2003dh has higher velocity ejecta than SN 1998bw. The model used for SN 1997ef (model CO100E18; Mazzali et al. 2000; Table 1), on the other hand, has much too little mass at high velocities, and it does not yield a broad-lined spectrum similar to the observed one.

The next spectrum we attempted to fit is the MMT 2003 April 24 one (Matheson et al. 2003). The spectrum (rest-frame epoch ~23 days) still has broad lines, and it is almost as bright as the April 10 one, so that maximum probably occurred about halfway between the two epochs. If model CO138E50 is used, the photosphere falls in the flat inner part of the density distribution (model CO138E50 "turns over" at $v \sim 20,000$ km s^{-1}, which is above the position of the photosphere at this epoch). The rather flat density distribution just above the photosphere leads to very deep but narrow absorption lines, which are not like the observed spectrum. On the other hand, model CO100E18 still has too little mass at these velocities to give any significant spectral features for such large velocities at this relatively advanced epoch [at a similar epoch, SN 1997ef had a low $v(ph) = 10,000$ km s^{-1}]. The spectrum is therefore in the "transition" phase between SN 1998bw–like and SN 1997ef–like. Clearly, some kind of new model is required. Since it is not clear how such a model should behave, we deal first with the next epoch, which can yield indications about the inner part of the ejecta, and then come back to the April 24 spectrum to verify the results.

Our third spectrum was obtained with Subaru on 2003 May 10 (Kawabata et al. 2003), a rest-frame epoch ~36 days, and it resembles that of SN 1997ef at a comparable epoch. Indeed, model CO138E50 yields a narrow-lined spectrum, while a
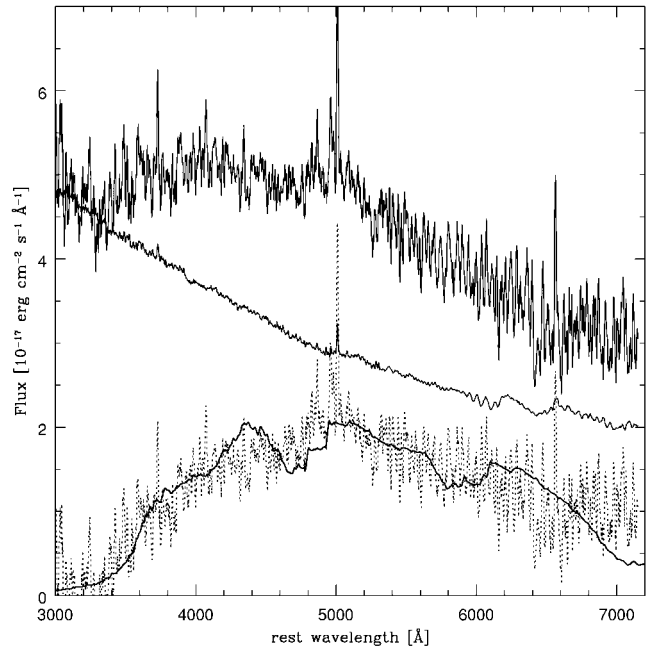

FIG. 1.—*Top*: Observed 2003 April 10 spectrum. *Middle*: Subtracted AG spectrum (observed on 2003 April 1. *Bottom*: "Net" SN spectrum (*dotted line*) and our synthetic spectrum (*thick solid line*).

much better synthetic spectrum is obtained using model CO100E18. This model, in fact, turns over at $v \sim 6000$ km s^{-1}, which is still below the photosphere at this epoch. However, model CO100E18 is too massive at the low velocities near the photosphere, resulting in strong back-warming and a high temperature. We tested different possibilities and found that a model where the density of CO100E18 is divided by a factor of 2 throughout (CO100E18/2) gives a good fit using $\log L = 42.43$ and $v(ph) = 7500$ km s^{-1} (Fig. 2). The synthetic spectrum has $V = -17.35$, $M(Bol) = -17.37$. At a comparable epoch, the values for SN 1998bw were $\log L =$
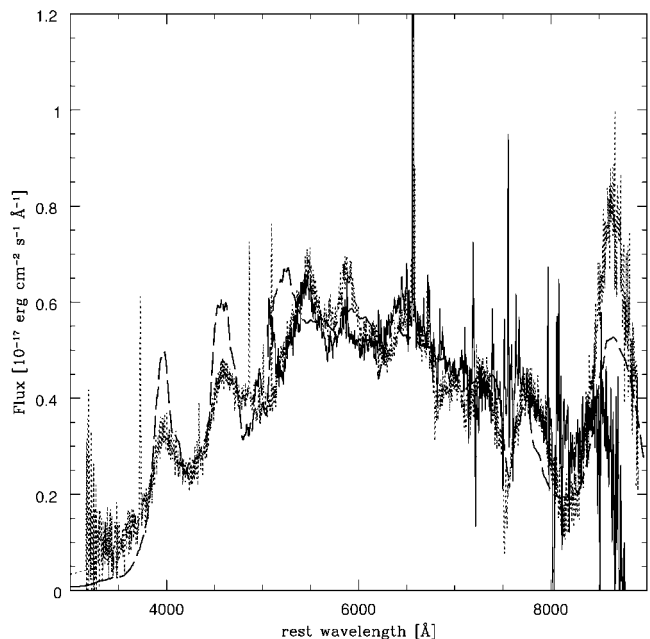

FIG. 2.—Observed 2003 May 10 spectrum (*thick solid line*), the spectrum of SN 1997ef obtained on 1998 January 1 (*dotted line*), and our synthetic spectrum (*thick dashed line*).
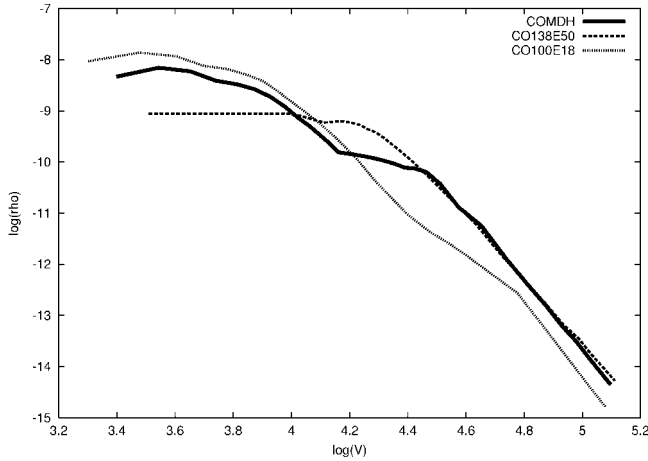
FIG. 3.—Density profiles of the various models

42.68 and v(ph) = 7500 km s^{-1}, and those for SN 1997ef were log L = 42.14 and v(ph) = 4900 km s^{-1}. Therefore, it appears that while model CO138E50 is adequate for the high-velocity part of the ejecta, a less energetic model such as CO100E18/2 is better suited for the low-velocity inner part. This might be expected given the shift in the properties of the spectrum.

The question is how those two models can be merged into one. We have adopted here an empirical approach. Model CO138E50 can be modified below v = 28,000 km s^{-1}, since this is below the photosphere of the April 10 spectrum, while model CO100E18/2 can be modified at velocities high enough that the May 10 spectrum is not affected. We tried different boundaries for this and finally chose v = 15,000 km s^{-1}. Therefore, we used model CO100E18/2 for v < 15,000 km s^{-1}, model CO138E50 for v > 25,000 km s^{-1}, and merged the two models linearly in between. The density structures of the various models are shown in Figure 3. With this new spherically symmetric "merged" model (COMDH), the results for April 10 and May 10 are essentially unchanged. COMDH has a smaller ejected mass than both CO138E50 and CO100E18, M_{ej} = 8 $M_\odot$, and E_{kin} = 3.8 × 10^{52} ergs, similar to CO138E50 as it is dominated by the high-velocity part. Since model COMDH is not computed from the hydrodynamics, but represents only a run of density versus velocity, multidimensional calculations are necessary to see how well it approximates a real multidimensional model.

The test for the merged model comes from fitting the April 24 spectrum, when the photosphere falls in the joining region. Using essentially the same parameters as discussed earlier [log L = 42.79 and v(ph) = 18,000 km s^{-1}], we could obtain a reasonably good fit to the observed spectrum (Fig. 4). The synthetic spectrum has V = −18.17, M(Bol) = −18.27. Therefore, considering all uncertainties, our merged model is probably a fair one-dimensional representation of the density structure of SN 2003dh.

3. A TWO-COMPONENT LIGHT-CURVE MODEL

In order to verify that the model we have constructed to reproduce the spectra is indeed valid, it is necessary to compute a light curve with it. Here we can follow the same approach as in the two-component models of Maeda et al. (2003), as this is essentially the same problem. Since we do not know the exact light curve of SN 2003dh, we only tried to reproduce the three points derived from the spectral fitting. These suggest
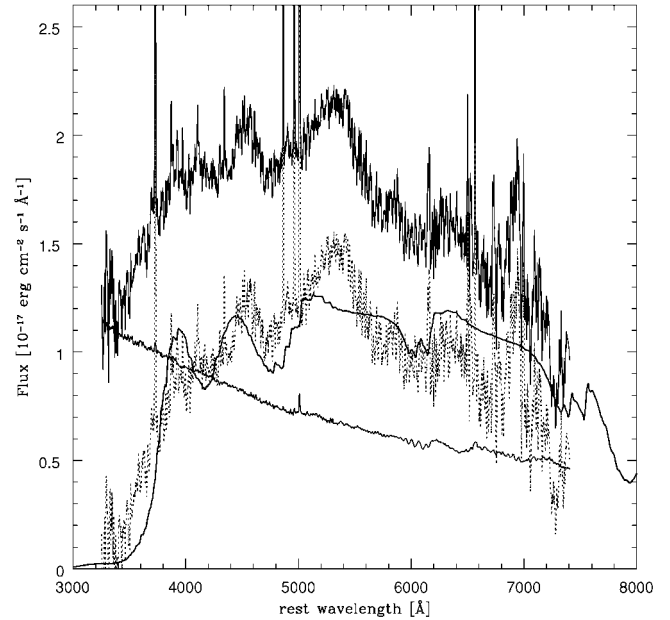

FIG. 4.—*Top*: Observed 2003 April 24 spectrum. *Middle*: Net SN spectrum (*dotted line*) and our synthetic spectrum (*thick solid line*). *Bottom*: Subtracted AG spectrum (observed on 2003 April 1).

a more rapid rise, a dimmer peak, and a faster decline than SN 1998bw, more similar to SN 2002ap.

We computed synthetic bolometric light curves for models CO138E50 and COMDH, using an LTE radiation transfer code and a gray gamma-ray transfer code (Iwamoto et al. 2000). The optical opacity was found to be dominated by electron scattering.

The synthetic light curve of CO138E50 with homogeneous mixing of ^{56}Ni out to 40,000 km s^{-1} is in reasonable agreement with the three points of SN 2003dh inferred from the spectra (Fig. 5). The mass of ^{56}Ni (0.32 $M_\odot$) is smaller than in the models for SN 1998bw (0.4–0.7 $M_\odot$: Nakamura et al. 2001; Iwamoto et al. 1998) and the mixing more extensive. The model light curve of SN 2003dh rises faster and peaks earlier than SN 1998bw.

The synthetic light curve computed with the merged model COMDH reproduces the three SN 2003dh points well for a ^{56}Ni mass of 0.35 $M_\odot$. Homogeneous mixing of ^{56}Ni out to
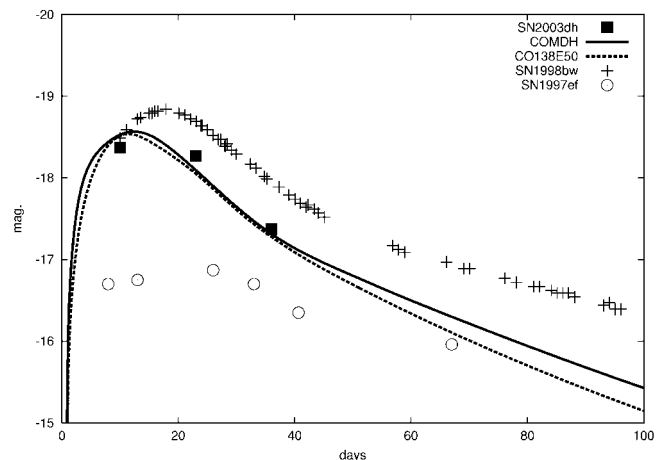

FIG. 5.—Observed and synthetic light curves. The bolometric light curve of SN 1998bw is from Patat et al. (2001), and that of SN 1997ef is from Mazzali, Iwamoto, & Nomoto (2000).

40,000 km s^{-1} was assumed, as for CO138E50. High-velocity ^{56}Ni is a feature that SN 2003dh shares with other hypernovae. It could be attributed to a jetlike asphericity in the explosion (Maeda et al. 2002; Maeda & Nomoto 2003; Woosley & Heger 2003).

The main feature of the merged model COMDH is the presence of a high-density region at low velocities, as derived from the spectral analysis. The effect of this region should be to slow down the decline of the late-time light curve. In SN 1998bw and other hypernovae, this is indeed observed starting at ~50 days and becoming more prominent later (Sollerman et al. 2000; Nomoto et al. 2001; Nakamura et al. 2001; Maeda et al. 2003). Figure 5 confirms that the synthetic light curve of model COMDH becomes somewhat brighter than that of CO138E50 at advanced phases. Although the merged model is favored because it gives reasonably good fits to both the light curve and the spectra, a definitive extraction of the light curve and further time coverage will be useful to distinguish between the models.

4. DISCUSSION

We have shown through spectral models that SN 2003dh was a hypernova. The high ejecta velocities observed in the early spectra require for the outer layers an explosion model similar to that used for SN 1998bw. However, at lower velocities such a model becomes too flat, and it is necessary to replace it with a lower energy one such as CO100, which has a steeper $\rho(v)$ at low velocities. From a spherically symmetric calculation, we obtain for SN 2003dh $E_{\rm kin} = 3.8 \times 10^{52}$ ergs, $M_{\rm ej} = 8\,M_\odot$, and $M(^{56}{\rm Ni}) = 0.35\,M_\odot$.

Woosley & Heger (2003) reached similar results. Their model parameters differ from ours somewhat, but they did not make detailed comparisons with observed data.

Our results suggest that SN 2003dh was intermediate between SNe 1997ef and 1998bw in $E_{\rm kin}$ release and ^{56}Ni production and that it ejected a comparable, possibly slightly smaller mass. Accounting for the compact remnant, the exploding star may have been a CO core of ~10–11 $M_\odot$, which implies a main-sequence mass of ~35–40 $M_\odot$. SN 2003dh seems to follow the relations between progenitor mass, $M(^{56}{\rm Ni})$ and $E_{\rm kin}$ (Nomoto et al. 2003).

All spherically symmetric models (including CO100 and CO138) are very flat inside, and they all have an inner mass-cut defining a "hole" in the density profile. Evidence for SNe 1997ef, 2002ap, and now 2003dh is that such a flat density distribution does not lend itself to successful spectrum synthesis. Actually, synthetic spectra computed for SN 1998bw beyond the epochs published in Iwamoto et al. (1998) are also not perfect, so this may be a common feature. Evidence for a slow-moving, oxygen-dominated inner region in SN 2003dh, to be obtained from the nebular spectra, would nicely confirm this picture.

The difficulties spherically symmetric explosion models encounter in reproducing the time evolution of hypernovae are almost certainly due to the inadequacy of such models when applied to phenomena that are intrinsically aspherical. Approximate studies suggest that asymmetries in the explosions may affect the light curves (Höflich, Wheeler, & Wang 1999; Woosley & Heger 2003). Therefore, the estimate of the explosion parameters may be subject to errors. In particular, $E_{\rm kin}$ may be overestimated by factors of a few by neglecting the fact that the highest velocity material is only ejected in a narrow cone, as discussed by Maeda et al. (2003) and recently by Woosley & Heger (2003) starting from the collapsar model. Both papers point at a similar scenario. According to Woosley & Heger (2003), if the high-velocity ejecta are contained in a cone with opening half-angle θ, $E_{\rm kin}$ is reduced by a factor $(1 - \cos\theta)$, and $M(^{56}{\rm Ni})$ required to fit the peak luminosity is also reduced by a factor $(1 - \cos\theta)/\sin^2\theta$ (in an extreme case). This is ≈ 0.5 if θ is small. The value of $M(^{56}{\rm Ni})$ can be derived from observations in the nebular phase, which is basically independent of geometry. At least for SN 1998bw, these confirmed that $M(^{56}{\rm Ni})$ estimated in spherical symmetry was correct within a factor of 2 or less (Nakamura et al. 2001; Maeda et al. 2002). Early-time spectra are less likely to be affected than the light curve, especially in the case of SN 2003dh, where the high-velocity material that dominates most spectral features is probably coming directly toward us. Nebular observations of SN 2003dh are urged.

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