

# LIGHT CURVE AND SPECTRAL MODELS FOR THE HYPERNOVA SN 1998bw ASSOCIATED WITH GRB 980425

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## ABSTRACT

A refined model for the unusual Type Ic supernova 1998bw, discovered as the optical counterpart to GRB 980425, is presented, and synthetic light curves and spectra are compared with the observations. The first 30 days of the light curve and the broad-line features of the spectra can be reproduced with the hydrodynamic model of the explosion of a  $14 M_{\odot}$  C + O star, the core of a star with initial mass  $40 M_{\odot}$ , assuming that the explosion was very energetic (kinetic energy  $E_K = 5 \times 10^{52}$  ergs) and that  $0.4 M_{\odot}$  of  $^{56}\text{Ni}$  were synthesized. At late times, however, the observed light-curve tail declines more slowly than this energetic model and is in better agreement with a less energetic ( $E_K = 7 \times 10^{51}$  ergs) one. This shift to a less energetic model may imply that the inner part of the ejecta has higher density and lower velocities than the model with  $E_K = 5 \times 10^{52}$  ergs, so that  $\gamma$ -rays deposit more efficiently. An aspherical explosion can produce such a structure of the ejecta. We also study detailed nucleosynthesis calculations for hyperenergetic supernova explosions and compare the yields with those of normal supernovae.

*Subject headings:* gamma rays: bursts — nuclear reactions, nucleosynthesis, abundances — supernovae: general — supernovae: individual (SN 1998bw)

## 1. INTRODUCTION

On 1998 April 25, GRB 980425 triggered the narrow field instrument (NFI) and wide field camera (WFC) detectors on board *BeppoSAX* (Soffita, Feroci, & Piro 1998). SN 1998bw was discovered within the WFC error box in the optical (Galama et al. 1998a) and radio wavelength bands (Kulkarni et al. 1998a) only 0.9 and 3 days after the date of the GRB, respectively. The X-ray afterglow detected by the NFI within the error box of GRB 980425 is consistent with SN 1998bw (Pian et al. 1999). The small likelihood of finding a supernova and a GRB in such a small field over such a short interval of time suggests that SN 1998bw and GRB 980425 are related (Galama et al. 1998b; Kulkarni et al. 1998b).

The early optical spectra of SN 1998bw apparently lack dominant line features, displaying only some broad emissions at 500, 620, and 800 nm (Galama et al. 1998b; Patat et al. 2000; Stathakis et al. 2000). These were shown to be the emission components of P Cygni profiles of very broad line blends. They are caused mostly by Fe II lines in the blue, by Si II near 600 nm, and by O I + Ca II near 720 nm (Iwamoto et al. 1998, hereafter IMN98). The absence of any hydrogen line after subtraction of the galaxy background and the fact that the Si II line at 615 nm has a very large velocity indicate that the supernova is neither a Type II nor a normal Type Ia (Galama et al. 1998b). Following the conventional classification scheme (Filippenko 1997), the lack of strong He I features led Patat & Piemonte (1998) to conclude that SN 1998bw is likely a Type Ic supernova (SN Ic) rather than a Type Ib.

The light curve of SN 1998bw (Galama et al. 1998b) showed a very early rise and reached a peak  $\sim 17$  days (in the *V* band) after the explosion and then has been declining exponentially with time (McKenzie & Schaefer 1999; Patat et al. 2000). This clearly indicates that the light curve is not a typical optical afterglow of a  $\gamma$ -ray burst, but it is powered by the radioactive decay of  $^{56}\text{Ni}$  and  $^{56}\text{Co}$  as in usual supernovae (IMN98). The distance modulus to SN 1998bw is estimated as  $\mu = 32.89$  mag, so that the peak luminosity of SN 1998bw is  $\sim 1 \times 10^{43}$  ergs  $\text{s}^{-1}$ , which is about 10 times brighter than typical SNe Ib/Ic (Clocchiatti & Wheeler 1997). To achieve such a high luminosity, a large amount of  $^{56}\text{Ni}$  must have been synthesized in SN 1998bw (IMN98; Woosley, Eastman, & Schmidt 1999), again, about 10 times as much as that produced in typical core-collapse-induced supernovae. The very broad spectral features and the light-curve shape led various groups to the conclusion that SN 1998bw had a very large kinetic energy of explosion  $E_K$  (IMN98; Woosley et al. 1999; Branch 2001).

IMN98 constructed models of the core-collapse-induced explosion of C + O cores of initially massive stars that had lost their hydrogen- and helium-rich layers before the explosion. Among those models, the energetic explosion [ $E_K \sim (2-5) \times 10^{52}$  ergs] of a C + O star of  $13.8 M_{\odot}$  successfully fitted the first 60 days of the light curve and early spectra, although the synthetic spectral lines were still narrower than the very broad, observed features (IMN98). Since the kinetic energy is more than 1 order of magnitude larger than the energy of typical supernovae, SN 1998bw was called a “hypernova” (IMN98), a term we use to describe events with  $E_K \gtrsim 10^{52}$  ergs, without specifying whether the central engine is a collider (MacFadyen & Woosley 1999), a magnetar (Nakamura 1998; Wheeler et al. 2000), or a pair-instability supernova.

Interestingly, photometry after  $\sim 60$  days showed that SN 1998bw declined significantly more slowly than the rate predicted by the model of IMN98 (McKenzie & Schaefer 1999; Patat et al. 2000). Also, the bolometric light curve has been constructed up to day 500 (Patat et al. 2000; Sollerman et al. 2000). Therefore, we have recomputed the light

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TABLE 1  
PARAMETERS OF THE C + O STAR MODELS

Model	$M_{\text{ms}}$ ( $M_{\odot}$ )	$M_{\text{C+O}}$ ( $M_{\odot}$ )	$M_{\text{ej}}$ ( $M_{\odot}$ )	$^{56}\text{Ni}$ Mass ( $M_{\odot}$ )	$M_{\text{cut}}$ ( $M_{\odot}$ )	$E_K$ ( $10^{51}$ ergs)
CO138E1 .....	$\sim 40$	13.8	12	0.4	2	1
CO138E7 .....	$\sim 40$	13.8	11.5	0.4	2.5	7
CO138E30 .....	$\sim 40$	13.8	10.5	0.4	3.5	30
CO138E50 .....	$\sim 40$	13.8	10	0.4	4	50

curve of SN 1998bw using progenitors of different masses and explosions of different energies, and we provide better estimates for these parameters.

The hydrodynamic models for SN 1998bw are described in § 2. Sections 3 and 4 are devoted to light-curve models and synthetic spectra models, respectively. Explosive nucleosynthesis in SN 1998bw is discussed in § 5. Finally, the nature of this peculiar supernova is summarized in § 6, with the emphasis being placed on possible evidence that the explosion was aspherical. Preliminary results have already been reported by Nakamura et al. (1999a, 2000) and Nomoto et al. (2000, 2001).

## 2. HYDRODYNAMIC MODELS FOR SN 1998bw

Hydrodynamic models are constructed as follows: C + O stars are chosen as progenitors, as in IMN98. Light curves and spectra are computed for various C + O star models with different values of the kinetic energy  $E_K$  and the ejecta mass  $M_{\text{ej}}$ . These parameters can be constrained by comparing calculated light curves, synthetic spectra, and photospheric velocities with the observational data of SN 1998bw as follows:

1. In the ordinary, low-energy SN Ic model (model CO138E1), a C + O star with a mass  $M_{\text{CO}} = 13.8 M_{\odot}$  (which is the core of a  $40 M_{\odot}$  main-sequence star; Nomoto & Hashimoto 1988; Nomoto et al. 1997) explodes with  $E_K = 1.0 \times 10^{51}$  ergs and  $M_{\text{ej}} = M_{\text{CO}} - M_{\text{cut}} \simeq 12 M_{\odot}$ . The variable  $M_{\text{cut}}$  ( $2 M_{\odot}$  in this case) denotes the position of the mass cut, which corresponds to the mass of the compact star remnant. This is either a neutron star or a black hole, depending on  $M_{\text{cut}}$ .

2. For the hypernova models CO138E50, CO138E30, and CO138E7, the progenitor C + O star of  $M_{\text{CO}} = 13.8$

$M_{\odot}$  is the same as in CO138E1. These models have different explosion energies:  $E_K = 5 \times 10^{52}$  ergs (CO138E50),  $3 \times 10^{52}$  ergs (CO138E30), and  $7 \times 10^{51}$  ergs (CO138E7). The ejecta mass is  $M_{\text{ej}} \simeq 10\text{--}11.5 M_{\odot}$ , i.e.,  $M_{\text{cut}} \simeq 2.5\text{--}4 M_{\odot}$ . The parameters of the models are summarized in Table 1. The position of the mass cut is chosen so that the ejected mass of  $^{56}\text{Ni}$  is the value required to explain the observed peak brightness of SN 1998bw by radioactive decay heating. The compact remnant in these hypernova models may well be a black hole, because  $M_{\text{cut}}$  can exceed, sometimes significantly, the maximum mass of a stable neutron star.

The hydrodynamics at early phases were calculated using a Lagrangian piecewise parabolic method (PPM) code (Colella & Woodward 1984). All models are spherically symmetric. The explosion is triggered by depositing thermal energy in several zones just below the mass cut so that the final kinetic energy has the required value. A strong shock wave forms and propagates toward the surface. Explosive nucleosynthesis takes place behind the shock wave. Radioactive  $^{56}\text{Ni}$  is produced in the deep, low-velocity layers of the ejecta.

In the SN II and SN Ib models, it has been demonstrated that Rayleigh-Taylor instabilities develop at the H/He and He/C + O interfaces and induce mixing of elements in the ejecta (see, e.g., Arnett, Fryxell, & Mueller 1989; Hachisu et al. 1991, 1994; Iwamoto et al. 1997). Although bare C + O stars, the progenitors of SNe Ic, lack composition interfaces with such pronounced density jumps, Rayleigh-Taylor instabilities can be driven by neutrino heating and develop at the Ni + Si/O interface (Kifonidis et al. 2000). In addition, polarization measurements suggested that SNe Ic, and hypernovae in particular, are asymmetric explosions (Danziger et al. 2000; Patat et al. 2000; Wang et al. 2001).

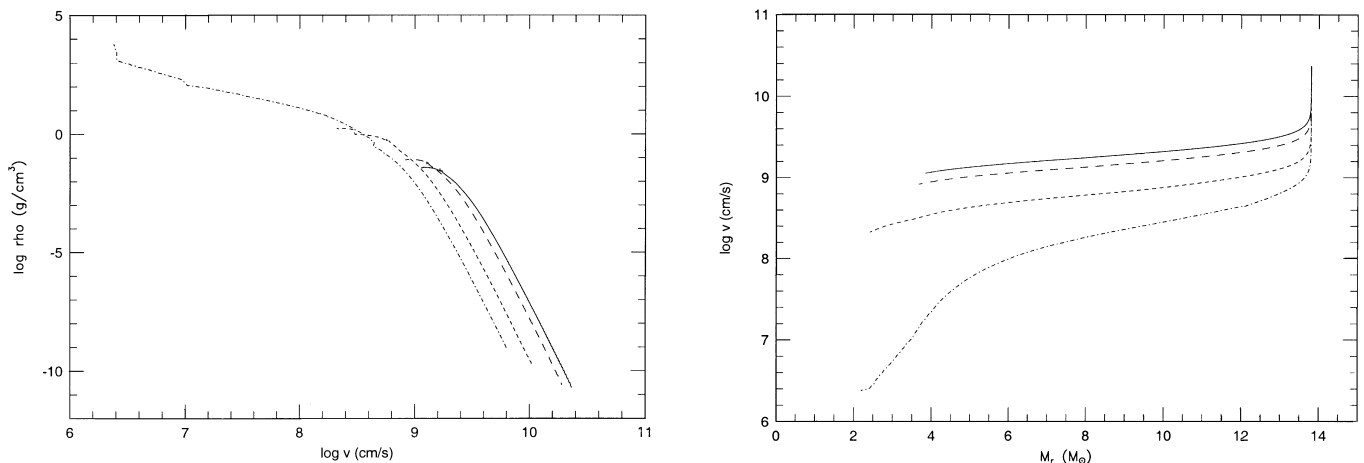


FIG. 1.—Density distributions against the velocity of homologously expanding ejecta (left) and the velocity profiles against the enclosed mass (right) for CO138E50 (solid line), CO138E30 (long-dashed line), CO138E7 (short-dashed line), and CO138E1 (dash-dotted line) at  $t = 250$  s.

The asymmetry of the explosion may reinforce the instability and bring heavy elements up to high-velocity layers. This is particularly true of jetlike explosions, where it is likely that extensive mixing takes place in velocity space. In view of the large uncertainties in our knowledge of the mixing process, we assume that the material ejected is uniformly mixed out to a velocity  $v = v_{\text{mix}}$ .

The hydrodynamic models become homologous ( $v \propto r$ ) at  $t \sim 250$  s and are then used as input for a radiation transfer code. The lines in Figure 1 show the density-velocity distribution of the homologously expanding ejecta (*left-hand panel*) and the enclosed mass  $M$ , as a function of velocity (*right-hand panel*) for models CO138E50 (*solid line*), CO138E30 (*long-dashed line*), CO138E7 (*short-dashed line*), and CO138E1 (*dash-dotted line*).

### 3. LIGHT-CURVE MODELS

Synthetic light curves are computed with a radiative transfer code (Iwamoto et al. 2000) that takes into account the balance between photoionizations and recombinations and includes a simplified treatment of line opacity. The width of the light-curve peak,  $\tau_{\text{LC}}$ , depends on  $E_K$  and  $M_{\text{ej}}$  approximately as  $\tau_{\text{LC}} \sim (\kappa/c)^{1/2} M_{\text{ej}}^{3/4} E_K^{-1/4}$ , where  $\kappa$  and  $c$  are the optical opacity and the speed of light, respectively (Arnett 1982). This means that the light curve can be reproduced with different explosion models that have the same values of  $M_{\text{ej}}^3 E_K^{-1}$ . However, these parameters can be further constrained from both photospheric velocities and spectra because the velocity scales roughly as  $M_{\text{ej}}^{-1/2} E_K^{1/2}$ . The light-curve shape depends also on the distribution of the radioactive heating source  $^{56}\text{Ni}$ , for which we examine the dependence on  $v_{\text{mix}}$  (§ 2).

Our calculations are compared with the bolometric light curve of SN 1998bw constructed by Patat et al. (2000), which uses a redshift distance  $\mu = 32.89$  mag ( $d = 37.8$  Mpc,  $H_0 = 65$  km s $^{-1}$  Mpc $^{-1}$ ) and  $A_V = 0.05$  mag. The time of core collapse is set at the detection of GRB 980425. Figure 2 shows the bolometric light curves of the energetic models CO138E50 (*solid line*) and CO138E30 (*long-dashed line*),

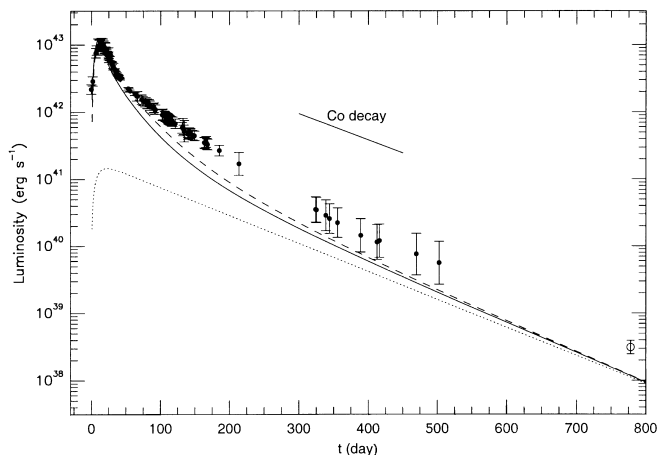


FIG. 2.—Light curves of CO138E50 ( $E_K = 5 \times 10^{52}$  ergs: *solid line*) and CO138E30 ( $E_K = 3 \times 10^{52}$  ergs: *long-dashed line*) compared with the bolometric light curve of SN 1998bw (Patat et al. 2000). A distance modulus of  $\mu = 32.89$  mag and  $A_V = 0.05$  are adopted. The dotted line indicates the energy deposited by positrons for CO138E50. The *HST* observation at day 778 (Fynbo et al. 2000) is shown by assuming negligible bolometric correction.

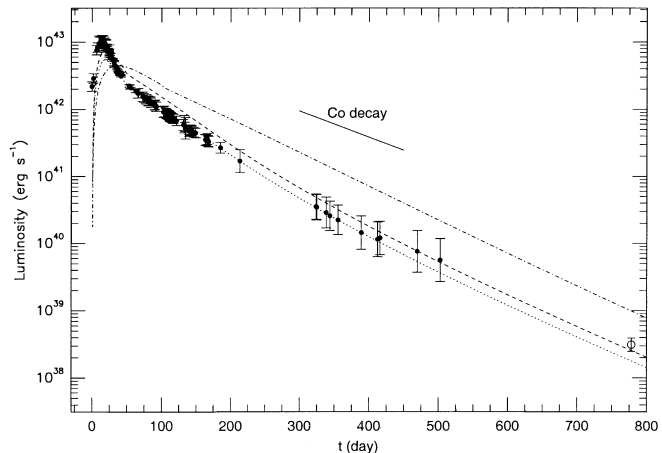


FIG. 3.—Light curves of CO138E7 ( $E_K = 7 \times 10^{51}$  ergs: *dashed line*) and CO138E1 ( $E_K = 1 \times 10^{51}$  ergs: *dash-dotted line*) compared with the bolometric light curve of SN 1998bw (Patat et al. 2000). Also shown is the light curve of modified CO138E7 with smaller  $^{56}\text{Ni}$  mass of  $0.28 M_\odot$  (*dotted line*). The *HST* observation at day 778 (Fynbo et al. 2000) is shown by assuming negligible bolometric correction.

and Figure 3 the less energetic models CO138E7 (*short-dashed line*) and CO138E1 (*dash-dotted line*).

Figure 4 shows the evolution of the calculated photospheric velocities of CO138E50 (*solid line*), CO138E30 (*long-dashed line*), CO138E7 (*short-dashed line*), and CO138E1 (*dash-dotted line*) compared with those obtained from spectral models (*filled circles*) and with the observed velocity of the Si II 635.5 nm doublet measured in the spectra at the absorption core (*open circles*; Patat et al. 2000) and that of the Ca II H + K doublet measured in the spectrum of May 23 (*square*; Patat & Piemonte 1998).

#### 3.1. Early Phase

The early part of the light curve ( $t \lesssim 25$  days) is well reproduced by the two energetic models, CO138E50 and

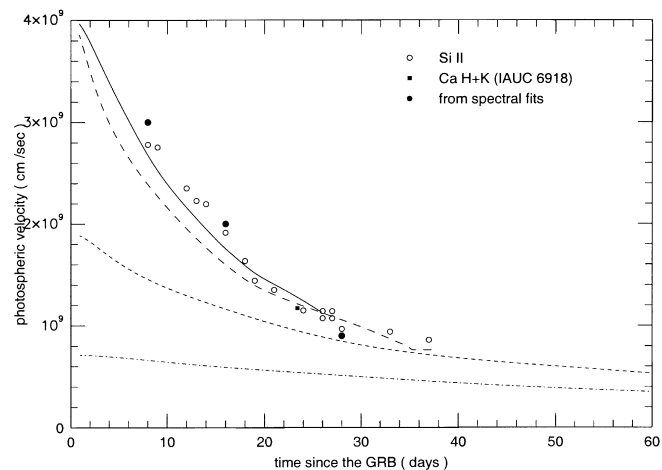


FIG. 4.—Photospheric velocities of CO138E50 (*solid line*), CO138E30 (*long-dashed line*), CO138E7 (*short-dashed line*), and CO138E1 (*dash-dotted line*) compared with the observations of SN 1998bw. Shown are the photospheric velocities obtained from spectral models (*filled circles*; this work), the observed velocity of the Si II 634.7, 637.1 nm lines measured in the spectra at the absorption core (*open circles*; Patat et al. 2000), and that of the Ca II H + K doublet measured in the spectrum of May 23 (*square*; Patat & Piemonte 1998).

CO138E30. The difference between the two curves is too small to see on the scale of Figure 2 because the light-curve width scales as  $E_K^{-1/4}$ . The early part of the light curve also depends on the  $^{56}\text{Ni}$  distribution in the ejecta. To reproduce the early sharp rise of the light curve, extensive mixing of  $^{56}\text{Ni}$ , out to  $v_{\text{mix}} = 22,000 \text{ km s}^{-1}$  for CO138E50 and  $v_{\text{mix}} = 30,000 \text{ km s}^{-1}$  for CO138E30, is required. A better fit can be obtained if we adopt the following ad hoc  $^{56}\text{Ni}$  distribution:  $X(^{56}\text{Ni}) = 0.79$  at  $v \leq 11,000 \text{ km s}^{-1}$ ,  $0.011$  at  $v = 11,000\text{--}17,000 \text{ km s}^{-1}$ , and  $0.032$  at  $v = 17,000\text{--}40,000 \text{ km s}^{-1}$ , where  $X(^{56}\text{Ni})$  denotes the mass fraction of  $^{56}\text{Ni}$ . The result is shown in Figure 5. Such a nonuniform distribution of  $^{56}\text{Ni}$  might be due to the mixing caused by Rayleigh-Taylor instability (§ 2) or reflect a complicated structure of possible jetlike ejecta (§ 6). The  $^{56}\text{Ni}$  mass is determined to be  $0.4 M_\odot$  from the fitting of the maximum luminosity (note that IMN98 slightly overestimated the mass of  $^{56}\text{Ni}$  because they assumed that the bolometric correction is negligible and adopted a different absorption and distance). In contrast, the early light curves of the less energetic models (CO138E7 and CO138E1) evolve too slowly, reaching the maximum too late, as compared to the observations (Fig. 3), even if  $^{56}\text{Ni}$  is distributed uniformly throughout the ejecta.

The photospheric velocities  $v_{\text{ph}}$  provide clearer diagnostics to distinguish between CO138E50 and CO138E30. In particular, in the early phase ( $t < 20$  days), the  $v_{\text{ph}}$  of CO138E50 is in good agreement with the observed  $v_{\text{ph}}$ , while the  $v_{\text{ph}}$  of CO138E30 is clearly too low to be consistent with the observations (Fig. 4).

In the early phase, therefore, model CO138E50 shows the best agreement with both the light curve and the photospheric velocities of SN 1998bw. The synthetic spectra also require the most energetic model CO138E50, as will be shown in § 4. CO138E50 has the same mass as the best model in IMN98 but a larger  $E_K$ , which is necessary, especially to improve the fit to the spectra (§ 4).

### 3.2. Intermediate Phase

At intermediate phases ( $t \sim 25\text{--}200$  days), the decline rate of the light curve is determined mainly by the fraction of the  $\gamma$ -rays emitted by  $^{56}\text{Co}$  decay that are trapped in the ejecta. The optical depth of the ejecta to the  $\gamma$ -rays scales as

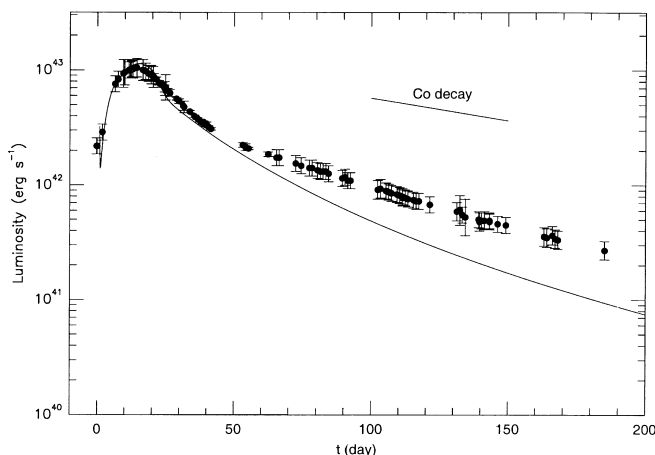


FIG. 5.—Early light curves of model CO138E50 with modified  $^{56}\text{Ni}$  distribution (see text) compared with the bolometric light curve of SN 1998bw (Patat et al. 2000).

$\kappa_r \rho R \propto M R^{-2} \propto M^2 E_K^{-1} t^{-2}$ . Thus, the behavior of the various models can be seen more easily than at earlier phases as follows:

1. The light curve of CO138E50 is consistent with SN 1998bw until day 50 but declines faster than the observation afterward (Fig. 2; McKenzie & Schaefer 1999; Patat et al. 2000). The light curve of CO138E30 declines more slowly than that of CO138E50 and is in better agreement with SN 1998bw, but it still declines faster than the observations.
2. The photospheric velocity  $v_{\text{ph}}$  shows a similar tendency. Figure 4 shows that the  $v_{\text{ph}}$  of CO138E50 is the best fit to the data for the first 20 days, but afterward the  $v_{\text{ph}}$  of CO138E30 gives as good a fit. The other two models do not fit the  $v_{\text{ph}}$  at all.
3. Figure 3 shows that the apparently exponential decline of SN 1998bw after day 60 (McKenzie & Schaefer 1999; Patat et al. 2000) is well reproduced by the lower energy model CO138E7. In this model,  $\gamma$ -ray trapping is more efficient than CO138E50 and CO138E30, but the observed low flux level at this phase requires a reduced  $^{56}\text{Ni}$  mass of  $0.28 M_\odot$  (dotted line). Note, however, that  $0.28 M_\odot$  of  $^{56}\text{Ni}$  is too small to reproduce the observed light-curve maximum. Note also that because of the interplay of  $E_K$  and  $M(\text{Ni})$ , it is difficult to establish those parameters from the intermediate-phase light curve alone.
4. The normal SN Ic model CO138E1 in Figure 3 is slow enough to trap most of the  $\gamma$ -rays emitted from the  $^{56}\text{Co}$  decay. The decline of the light curve is therefore too slow compared to the observed rate.

These comparisons between SN 1998bw and the model light curves and  $v_{\text{ph}}$  in Figures 2, 3, and 4 indicate that  $\gamma$ -ray deposition after about day 50 in SN 1998bw is more efficient than predicted by CO138E50 and -E30, although these models give an appropriate description of the early light curve and spectra. Higher deposition can be achieved if there exists a significant amount of low-velocity and high-density material. Indications of the presence of a low-velocity, high-density region suggest that the ejecta distribution is not spherically symmetric, as will be discussed in § 6. We note that such indications are also found for SN 1997ef (Iwamoto et al. 2000; Mazzali, Iwamoto, & Nomoto 2000), a lower energy analogue of SN 1998bw.

### 3.3. Late Phase

After day  $\sim 200$  the decline of the model light curve becomes slower, and it approaches the half-life of  $^{56}\text{Co}$  decay around day 400. At  $t \gtrsim 400$  days most  $\gamma$ -rays escape from the ejecta. The  $\gamma$ -ray deposition fraction at 400 days is 1%, 1.5%, 6%, and 13% for CO138E50, -E30, -E7, and -E1, respectively. On the other hand, kinetic energies of positrons emitted from the decay of  $^{56}\text{Co}$  are supposed to be fully thermalized because of the postulated weak magnetic field (see, e.g., Colgate & Petchek 1979). Therefore, positron kinetic energy deposition determines the light curve at  $t \gtrsim 400$  days (dotted line in Fig. 2). Here the luminosity by positron deposition is given as

$$L(\text{Co}, e^+) = 1.4 \times 10^{43} \left[ \frac{M(\text{Ni})}{1 M_\odot} \right] \times \exp\left(\frac{-t}{111.26 \text{ days}}\right) 0.035 \text{ ergs s}^{-1}, \quad (1)$$

where the positron fraction in energy is 3.5% (see, e.g., Axelrod 1980; see Cappellaro et al. 1997 and Milne, The, & Leising 1999 for the light curves including positron escape). If the observed tail should follow the positron-powered light curve, the  $^{56}\text{Co}$  mass could be determined directly. Since positron deposition should occur almost on the spot, this determination does not depend much on any asphericity of the ejecta.

On 2000 June 11, which corresponds to an SN epoch of  $t = 778$  days, *Hubble Space Telescope* (HST) observations detected a pointlike source at the position of SN 1998bw (Fynbo et al. 2000). The observed magnitude ( $V_{\text{mag}} = 25.41 \pm 0.25$ ) is consistent with the prediction of CO138E7 (Fig. 2) but brighter than CO138E50 (Fig. 3). The observed luminosity would even be higher than CO138E7 if the bolometric correction was significant. In any case, these comparisons suggest that the positron contribution is not dominant yet around day 800.

#### 4. SYNTHETIC SPECTRA

In Figure 6 we show the synthetic spectra obtained for the same three epochs fitted in IMN98 (*solid lines*) compared with spectra observed at ESO (*heavy lines*). We used model CO138E50 and computed synthetic spectra with a Monte Carlo model (Mazzali & Lucy 1993), improved with the inclusion of photon branching and a new extended and improved line list (Lucy 1999; Mazzali 2000). The synthetic spectra were computed using the luminosity derived from the light curve, a distance modulus of  $\mu = 32.89$  mag, and  $A_V = 0.05$ . The assumption of low reddening is supported by the upper limit of  $0.1 \text{ \AA}$  in the equivalent width of the Na I D line obtained from high-resolution spectra (Patat et al. 2000). The observed spectra used here (*solid lines*) are the “definitive,” fully reduced version of the same ESO spectra shown in IMN98 and are calibrated with respect to the  $V$

photometry. The residual correction factors for the other bands are usually very close to 1, but they are  $\sim 1.1$  for  $B$  in the May 11 and 23 spectra. Therefore, the new models (i.e., the three epochs of CO138E50), have somewhat different parameters than those of IMN98. Both the luminosities and the photospheric velocities are larger than in IMN98. The photospheric velocity is now in better agreement with the measured velocity of the Si II line (IMN98; Fig. 3).

The synthetic spectra clearly improve over those of IMN98, especially at the earliest epochs. Absorptions not caused by broad blends of many lines of moderate strength, such as the Si II feature near  $6000 \text{ \AA}$  and, in particular, the O I + Ca II feature between  $7000$  and  $8000 \text{ \AA}$ , are now much broader, in significantly better agreement with the data. Nevertheless, the blue sides of those absorptions are still too narrow, indicating that even the new model CO138E50 may not contain enough mass at the highest velocities.

Therefore, we introduced an arbitrary change to the original CO138E50 density structure. Several possibilities were tested, and improved results were obtained when the density slope was reduced from  $\rho \propto r^{-8}$  to  $\rho \propto r^{-6}$  at  $v > 30,000 \text{ km s}^{-1}$ . This does not introduce a significant change in  $M_{\text{ej}}$  and increases  $E_K$  by only about 10%, but it does increase the density at high velocities, leading to significant absorption at  $v \sim 60,000 \text{ km s}^{-1}$  in the strongest lines, especially the Ca II IR triplet, extending the absorption troughs to the blue. The corresponding synthetic spectra are shown as dotted lines in Figure 6. The effect of the change is of course largest at the earliest epochs. Although the overall agreement with the observed spectra is better, several problems remain, the most severe of which is clearly the excessive strength of the O I line at  $7200 \text{ \AA}$  on May 11 and 23. The composition of the highest velocity ejecta is dominated by O in our one-dimensional models, and it is difficult to make that line become weaker. On May 23, the synthetic Ca II IR triplet matches the weak feature at  $8000 \text{ \AA}$ , which is first seen on May 11 and which continues to grow until it finally causes the wavelength of the absorption minimum of the entire broad feature to shift to  $\sim 8200 \text{ \AA}$  (Patat et al. 2000). This is a rather peculiar behavior because on May 3 the O I and Ca II lines had to blend much more to give rise to the observed broad feature, which then had a minimum at  $7000 \text{ \AA}$ . The synthetic O I line is too strong and too fast. The core of the broad feature, if it is interpreted as O I  $7774 \text{ \AA}$ , indicates a velocity of  $10,500 \text{ km s}^{-1}$  on May 11 and  $6000 \text{ km s}^{-1}$  on May 23. This is significantly lower than the corresponding velocity of the model photosphere. Actually, the definition of a photosphere at very red wavelengths is not very accurate because the density of spectral lines is low and so line opacity does not define a pseudocontinuum in that region. Therefore, the observations probably indicate that a large fraction of the O is located at low velocities.

A very flat ( $\rho \propto r^{-2}$ ) density distribution was also used by Branch (2001) to fit the spectrum of SN 1998bw. This dependence is, however, too flat when we use our MC model because the ionization of, e.g., Ca II does not fall as steeply as he assumed. On the other hand, Branch's value of  $E_K$  ( $5 \times 10^{52}$  ergs) is similar to ours, but he quotes a mass of  $6 M_{\odot}$  above  $7000 \text{ km s}^{-1}$ , while in our case the mass above that velocity is as large as  $\sim 10 M_{\odot}$ . Such a flat density distribution at high velocities is also required to fit the spectrum of another hypernova, SN 1997ef (Mazzali et al. 2000). This might indicate that the progenitors of these hyper-

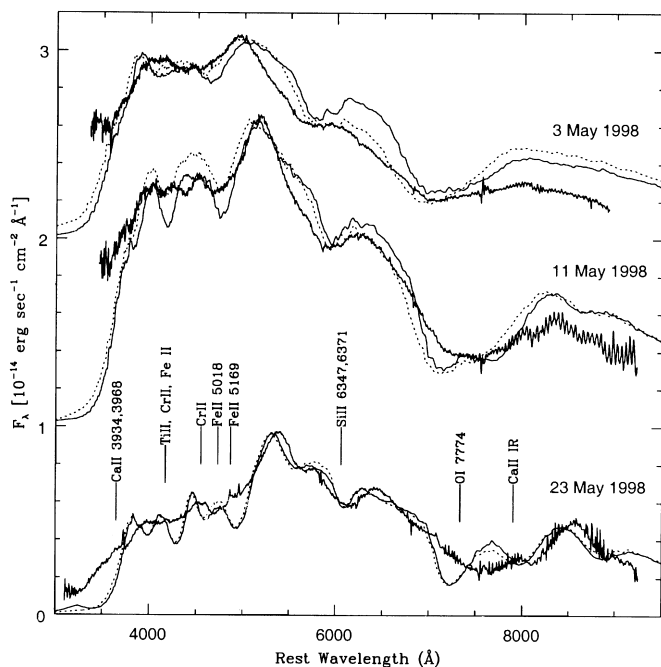


FIG. 6.—Three ESO spectra of SN 1998bw near maximum (*heavy lines*) are compared with synthetic spectra obtained using model CO138E50 (*solid lines*) and with spectra obtained for a modified density distribution as described in the text (*dotted lines*).

novae underwent very extensive mass loss; the outer density structure of the ejecta is flatter than that of ordinary giants and comparable to that of a mass-losing star.

Clearly, a definitive solution has not been found yet. It is quite possible that only by taking into account departures from spherical symmetry will it be possible to obtain a really accurate fit to the spectra. Nevertheless, considering the complexity of the problem, our fits at least demonstrate that a large  $E_K$  is necessary and that the O-dominated composition of the SN Ic model yields quite a reasonable reproduction of the observations.

### 5. EXPLOSIVE NUCLEOSYNTHESIS

We calculated explosive nucleosynthesis using a detailed nuclear reaction network (Thielemann, Nomoto, & Hashimoto 1996; Nakamura et al. 1999b). Our calculations are performed in two steps. The first step is a hydrodynamic simulation of the explosion with a small nuclear reaction network containing only 13  $\alpha$ -nuclei ( $^4\text{He}$ ,  $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{20}\text{Ne}$ ,  $^{24}\text{Mg}$ ,  $^{28}\text{Si}$ ,  $^{32}\text{S}$ ,  $^{36}\text{Ar}$ ,  $^{40}\text{Ca}$ ,  $^{44}\text{Ti}$ ,  $^{48}\text{Cr}$ ,  $^{52}\text{Fe}$ , and  $^{56}\text{Ni}$ ), as described in § 2. In the second step, postprocessing calculations are performed at each mesh point of the hydrodynamic model with the extended reaction network (Hix & Thielemann 1996), which contains 211 isotopes up to  $^{71}\text{Ge}$ .

The top panel of Figure 7 shows the isotopic composition of the ejecta of the hypernova model CO138E50 as a function of the enclosed mass  $M_r$  and of the expansion velocity. The nucleosynthesis in other hypernova and supernova models (CO138E30, CO138E7, CO138E1) is also shown in Figure 7 for comparison. The yields of the hypernova and supernova models are summarized in Table 2. Table 3 and Figure 8 give more detailed yields and the abundances, respectively, of stable isotopes relative to the solar values for model CO138E50. From these figures and tables, we note the following characteristics of nucleosynthesis of hyperenergetic explosions compared with normal energy explosions:

1. The complete Si-burning region where  $^{56}\text{Ni}$  is produced is extended farther out (in mass coordinates) as the explosion energy increases. How much processed matter is ejected from this region depends on the mass cut. Compared with normal core-collapse supernovae, the much larger amount of  $^{56}\text{Ni}$  ( $\sim 0.4 M_\odot$ ) observed in SN 1998bw implies that the mass cut is deeper, so that the elements synthesized in this region, such as  $^{59}\text{Cu}$ ,  $^{63}\text{Zn}$ , and  $^{64}\text{Ge}$  (which decay into  $^{59}\text{Co}$ ,  $^{63}\text{Cu}$ , and  $^{64}\text{Zn}$ , respectively), are ejected more abundantly. Among hypernova models, more energetic models produce more  $^{56}\text{Ni}$  in the incomplete Si-

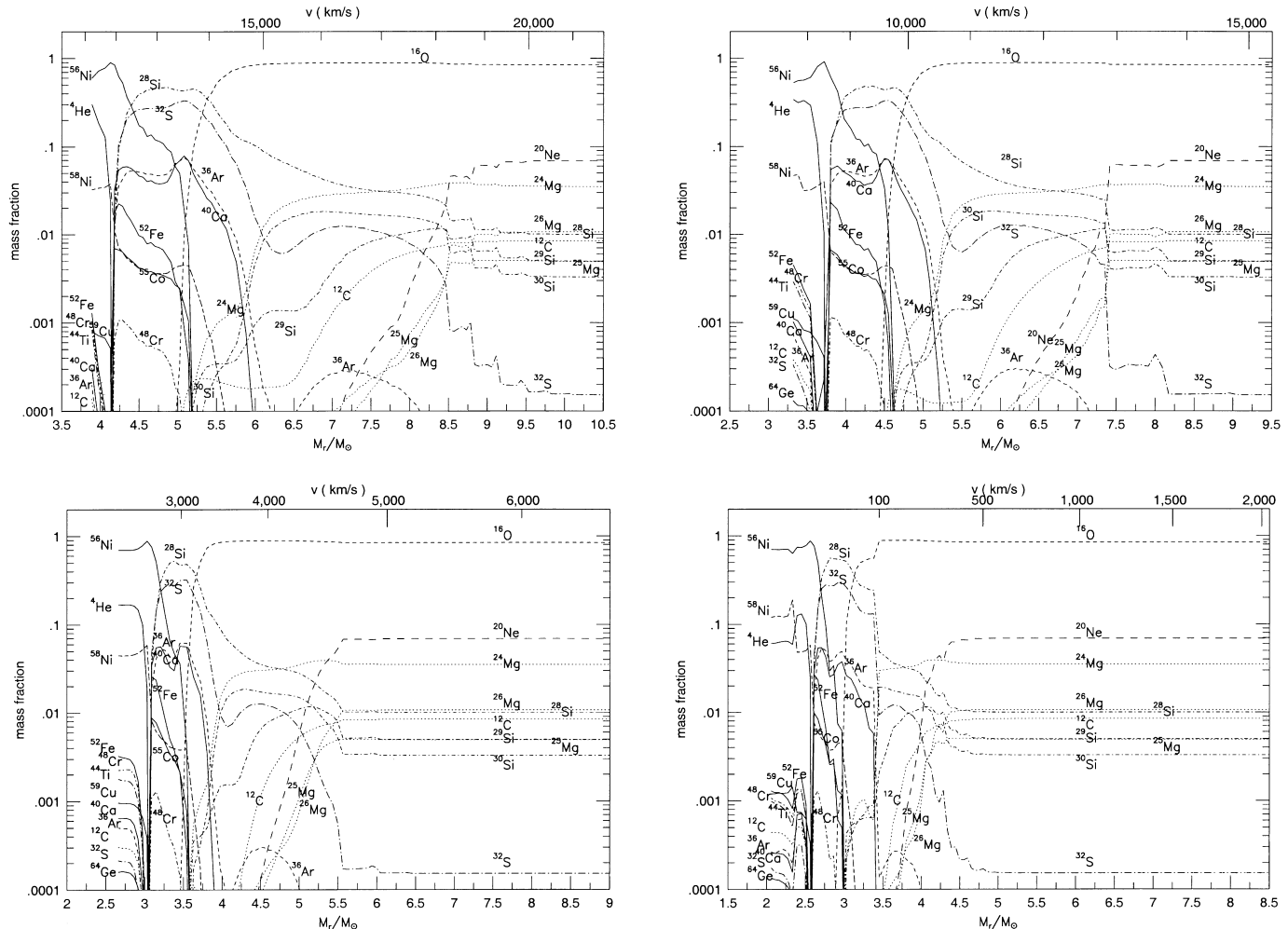


FIG. 7.—Isotopic composition of ejecta of hypernovae ( $E_K = 5 \times 10^{52}$  ergs: top left;  $E_K = 3 \times 10^{52}$  ergs: top right;  $E_K = 7 \times 10^{51}$  ergs: bottom left) and usual supernovae ( $E_K = 1 \times 10^{51}$  ergs: bottom right). Only the dominant species are plotted. The explosive nucleosynthesis is calculated using a detailed nuclear reaction network including a total of 211 isotopes up to  $^{71}\text{Ge}$ .

TABLE 2  
YIELDS OF HYPERNOVA AND SUPERNOVA MODELS

Model	C	O	Ne	Mg	Si	S	Ca	Ti	Fe	Ni	<sup>44</sup> Ti	<sup>56</sup> Ni	<sup>57</sup> Ni
CO138E1 .....	0.10	8.9	0.66	0.51	0.52	0.19	0.023	0.0007	0.44	0.065	$3.4 \times 10^{-4}$	0.40	0.016
CO138E7 .....	0.09	8.5	0.58	0.47	0.52	0.19	0.029	0.0010	0.44	0.036	$4.5 \times 10^{-4}$	0.40	0.014
CO138E30 .....	0.07	7.6	0.44	0.38	0.74	0.35	0.054	0.0009	0.45	0.023	$2.3 \times 10^{-4}$	0.40	0.012
CO138E50 .....	0.06	7.1	0.37	0.34	0.83	0.41	0.066	0.0007	0.46	0.018	$5.5 \times 10^{-5}$	0.40	0.011

NOTE.—All values are in units of  $M_{\odot}$ .

burning region (see point 3 below), and thus  $M_{\text{cut}}$  is larger to eject  $\sim 0.4 M_{\odot}$   $^{56}\text{Ni}$  as constrained from the light curve of SN 1998bw (Fig. 7).

2. In the complete Si-burning region of the hypernova models (CO138E50/E30), elements produced by  $\alpha$ -rich freezeout are enhanced because nucleosynthesis proceeds at lower densities than in CO138E1. Figure 7 clearly shows a trend that a larger amount of  $^4\text{He}$  is left in more energetic explosions. Hence, the mass fractions of the species synthesized through  $\alpha$ -particle capture, such as  $^{44}\text{Ti}$  and  $^{48}\text{Cr}$  (which decay into  $^{44}\text{Ca}$  and  $^{48}\text{Ti}$ , respectively) are larger in

CO138E50/E30/E7 than CO138E1. The integrated mass of these species depends on  $M_{\text{cut}}$ . For CO138E50, the ejected mass of  $^{44}\text{Ti}$  is smaller than in other models because of its larger  $M_{\text{cut}}$ . Note that the  $^4\text{He}$  produced even in the most energetic models has a velocity significantly smaller than that of the He shell identified in SN 1998bw at a velocity of  $18,300 \text{ km s}^{-1}$  by Patat et al. (2000) on the basis of near-IR spectra. Spectral evidence for low-velocity He in SN 1998bw is unclear; however, the distribution of He depends on mixing in velocity space.

3. The incomplete Si-burning region is more massive in more energetic explosions. The main products in this region are  $^{28}\text{Si}$ ,  $^{32}\text{S}$ , and  $^{56}\text{Ni}$ . CO138E50 produces  $0.2 M_{\odot}$  of  $^{56}\text{Ni}$  in this region. Other important species such as  $^{52}\text{Fe}$ ,  $^{55}\text{Co}$ , and  $^{51}\text{Mn}$  (decaying into  $^{52}\text{Cr}$ ,  $^{55}\text{Mn}$ , and  $^{51}\text{V}$ , respectively) are synthesized more abundantly in the more energetic explosions.

4. For the larger explosion energy, oxygen burning takes place in more extended, lower density regions. O, C, and Al are burned more efficiently in these cases, and the abundances of the elements in the ejecta are smaller, while a larger amount of ash products such as Si, S, and Ar are synthesized by oxygen burning.

## 6. CONCLUSIONS AND DISCUSSION

In this paper we have presented a model for SN 1998bw that is in better agreement with the early observations than the previous model in IMN98. Models with different  $E_K$  yield different synthetic spectra, and by comparing them with the observed early-time spectra of SN 1998bw and trying to fit the very broad absorption features, we selected model CO138E50 with  $M_{\text{ej}} = 10 M_{\odot}$  and  $E_K = 5 \times 10^{52}$  ergs as the best match to the early data. The large value of  $E_K$  qualifies SN 1998bw as “the” Type Ic hypernova (SN

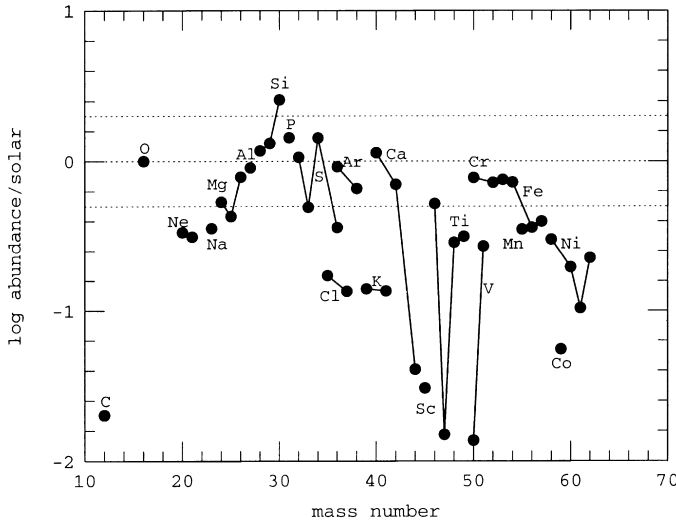


FIG. 8.—Abundances of stable isotopes relative to the solar values for model CO138E50.

TABLE 3  
DETAILED YIELDS OF MODEL CO138E50

Isotope	Value ( $M_{\odot}$ )	Isotope	Value ( $M_{\odot}$ )	Isotope	Value ( $M_{\odot}$ )	Isotope	Value ( $M_{\odot}$ )	Isotope	Value ( $M_{\odot}$ )
<sup>12</sup> C .....	6.45E-02	<sup>13</sup> C .....	2.57E-08	<sup>14</sup> N .....	1.34E-07	<sup>15</sup> N .....	4.08E-08	<sup>16</sup> O .....	7.07
<sup>17</sup> O .....	1.76E-07	<sup>18</sup> O .....	2.45E-08	<sup>19</sup> F .....	1.12E-08	<sup>20</sup> Ne .....	3.72E-01	<sup>21</sup> Ne .....	1.10E-03
<sup>22</sup> Ne .....	5.49E-04	<sup>23</sup> Na .....	1.18E-02	<sup>24</sup> Mg .....	2.57E-01	<sup>25</sup> Mg .....	2.76E-02	<sup>26</sup> Mg .....	5.78E-02
<sup>27</sup> Al .....	4.99E-02	<sup>28</sup> Si .....	7.27E-01	<sup>29</sup> Si .....	4.30E-02	<sup>30</sup> Si .....	5.70E-02	<sup>31</sup> P .....	6.93E-03
<sup>32</sup> S .....	3.88E-01	<sup>33</sup> S .....	1.48E-03	<sup>34</sup> S .....	2.46E-02	<sup>36</sup> S .....	2.12E-05	<sup>35</sup> Cl .....	5.17E-04
<sup>37</sup> Cl .....	1.39E-04	<sup>36</sup> Ar .....	7.10E-02	<sup>38</sup> Ar .....	1.00E-02	<sup>40</sup> Ar .....	2.85E-07	<sup>39</sup> K .....	4.26E-04
<sup>41</sup> K .....	3.21E-05	<sup>40</sup> Ca .....	6.61E-02	<sup>42</sup> Ca .....	2.83E-04	<sup>43</sup> Ca .....	4.60E-07	<sup>44</sup> Ca .....	5.53E-05
<sup>46</sup> Ca .....	5.53E-10	<sup>48</sup> Ca .....	7.90E-14	<sup>45</sup> Sc .....	1.02E-06	<sup>46</sup> Ti .....	1.09E-04	<sup>47</sup> Ti .....	2.96E-06
<sup>48</sup> Ti .....	5.87E-04	<sup>49</sup> Ti .....	4.90E-05	<sup>50</sup> Ti .....	4.15E-09	<sup>50</sup> V .....	1.00E-08	<sup>51</sup> V .....	8.39E-05
<sup>50</sup> Cr .....	5.11E-04	<sup>52</sup> Cr .....	9.53E-03	<sup>53</sup> Cr .....	1.16E-03	<sup>54</sup> Cr .....	3.07E-07	<sup>55</sup> Mn .....	4.32E-03
<sup>54</sup> Fe .....	4.92E-02	<sup>56</sup> Fe .....	4.01E-01	<sup>57</sup> Fe .....	1.07E-02	<sup>58</sup> Fe .....	1.04E-07	<sup>59</sup> Co .....	1.72E-04
<sup>58</sup> Ni .....	1.36E-02	<sup>60</sup> Ni .....	3.54E-03	<sup>61</sup> Ni .....	8.69E-05	<sup>62</sup> Ni .....	5.91E-04	<sup>64</sup> Ni .....	3.10E-13
<sup>63</sup> Cu .....	3.47E-07	<sup>65</sup> Cu .....	2.36E-07	<sup>64</sup> Zn .....	6.49E-06	<sup>66</sup> Zn .....	3.91E-06	<sup>67</sup> Zn .....	3.03E-09
<sup>68</sup> Zn .....	1.93E-09								

IIn 1997cy may be called a “Type IIn hypernova”; Germany et al. 2000; Turatto et al. 2000). The mass of the progenitor C + O star is  $13.8 M_{\odot}$ , corresponding to a main-sequence mass of  $\sim 40 M_{\odot}$ . All models require  $M(^{56}\text{Ni}) \sim 0.4 M_{\odot}$  to power the bright-light-curve peak.<sup>5</sup> This is about an order of magnitude larger than in typical core-collapse SNe. The compact remnant is probably a black hole because its mass exceeds  $\sim 3 M_{\odot}$  as constrained from the mass of  $^{56}\text{Ni}$ .

Although the early light curve of SN 1998bw ( $t \lesssim 50$  days) is reproduced well by the most energetic model CO138E50, the observed tail declines more slowly than this model does (§ 3). The lower energy model CO138E30 is in better agreement with observations at  $t \lesssim 100$  days, but it still declines too fast. Model CO138E7 has a slower tail and can reproduce the observed light-curve tail if a smaller  $^{56}\text{Ni}$  mass of  $0.28 M_{\odot}$  is adopted. This suggests that there might be a high-density core with low velocities in SN 1998bw where the  $\gamma$ -rays deposit efficiently.

Such a dense core could be formed in spherically symmetric models if the exploding star had a massive He envelope so that a strong reverse shock was formed at the C + O/He interface and largely decelerated the inner core as found in SN Ib models (Hachisu et al. 1991, 1994). However, the apparent absence of the He I lines in the optical spectra in SN 1998bw (Patat et al. 2000) is not consistent with the presence of such a massive He envelope. Also, late-time energy input from  $^{56}\text{Co}$  bubbles might create a nonhomologous structure. However, the energy from radioactive decay is much smaller than the large explosion energy of SN 1998bw ( $\sim 10^{52}$  ergs), so that its effect is negligible.

We suggest that the peculiar density distribution is the result of a nonspherically symmetric explosion. If the outburst in SN 1998bw took the form of a prolate spheroid, for example, the explosive shock was probably strong along the long axis, ejecting material with large velocities and producing abundant  $^{56}\text{Ni}$ , which might have caused the early bright-light curve. In directions away from the long axis, on the other hand, oxygen would not be consumed, and the density could be high enough for  $\gamma$ -rays to be trapped even at advanced phases, thus giving rise to the slowly declining tail. These features can be seen in the hydrodynamic models of jetlike explosions (Nagataki et al. 1997; Khokhlov et al. 1999; MacFadyen & Woosley 1999; Maeda et al. 2000). The fact that the late light curve is fitted by model

CO138E7 with  $0.28 M_{\odot}$  of  $^{56}\text{Ni}$ , while the early light curve requires as much as  $0.4 M_{\odot}$ , could also support this suggestion and point at the geometrical ratio between the extension of the high- and low-density regions.

There are several observations that support the above nonspherical explosion scenario. The observed polarization ( $\sim 0.5\%$ ) of the early optical light (IMN98; Patat et al. 2000) suggests that the ejecta of SN 1998bw is aspherical. The observed abnormal distribution of elements in velocity space as seen in the emission line profiles in the nebular phase, with significant amounts of O being located at lower velocity than Fe (Danziger et al. 2000; Nomoto et al. 2001; Patat et al. 2000) can better be explained if the explosion is nonspherically symmetric (Maeda et al. 2000).

The possible connection between SN 1998bw and GRB 980425 also supports the conjecture that SN 1998bw was aspherical. The energy of the photons produced by synchrotron emission at the relativistic shock is approximately given by  $h\nu \sim 160 \text{ keV} (\Gamma/100)^4 n_1^{1/2}$  (Piran 1999), where  $\Gamma$  is the Lorentz factor of the shock and  $n_1 (\text{cm}^{-3})$  is the density of the interstellar matter. In order to produce an observable GRB,  $\Gamma$  should be as large as  $\Gamma \sim 100$ . However, even the most energetic model (CO138E50) has only a very small mass of relativistic ejecta ( $\sim 10^{-10} M_{\odot}$  with  $\Gamma \geq 100$ ), although relativistic hydrodynamic calculations are necessary to obtain the accurate mass. Such a small amount of relativistic material, which is consistent with previous estimates (IMN98; Woosley et al. 1999), is not enough to produce GRB 980425 in a spherically symmetric model. However, if the explosion is axisymmetric, for instance, the energy can be carried by only a small fraction of the material, which might then attain a large Lorentz factor.

Regarding asphericity, we note that Danziger et al. (2000; see also Nomoto et al. 2001) estimated a  $^{56}\text{Ni}$  mass of  $0.35\text{--}0.65 M_{\odot}$  from the nebular lines of Fe of SN 1998bw. This estimate does not depend much on the asphericity and is in good agreement with the  $^{56}\text{Ni}$  mass of the spherical models CO138. On the other hand, Höflich, Wheeler, & Wang (1999) suggested that the  $^{56}\text{Ni}$  mass can be as small as  $0.2 M_{\odot}$  if aspherical effects are large. Because the difference between these results is not so large, aspherical effects might be modest in SN 1998bw. If the  $^{56}\text{Ni}$  mass could be determined more accurately from the late observations, it would provide a good measure of the degree of the asphericity.

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<sup>5</sup> After submitting this paper, Sollerman et al. (2000) was published. They found that  $^{56}\text{Ni}$  of  $\sim 0.3\text{--}0.9 M_{\odot}$  was necessary to power the late light curve based on the model CO138 (IMN98), which is consistent with our results.



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