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THE METAMORPHOSIS OF SN 1998bw

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ABSTRACT

We present and discuss the photometric and spectroscopic evolution of the peculiar SN 1998bw, associated with GRB 980425, through an analysis of optical and near-IR data collected at ESO—La Silla. The spectroscopic data, spanning the period from day −9 to day +376 (relative to B maximum), have shown that this supernova (SN) was unprecedented, although somewhat similar to SN 1997ef. Maximum expansion velocities as high as $3 \times 10^4$ km s$^{-1}$ to some extent mask its resemblance to other Type Ic SNe. At intermediate phases, between photospheric and fully nebular, the expansion velocities ($\sim 10^4$ km s$^{-1}$) remained exceptionally high compared to those of other recorded core-collapse SNe at a similar phase. The mild linear polarization detected at early epochs suggests the presence of asymmetry in the emitting material. The degree of asymmetry, however, cannot be decoded from these measurements alone. The H I 1.083 and 2.058 μm lines are identified, and He is suggested to lie in an outer region of the envelope. The temporal behavior of the fluxes and profiles of emission lines of Mg II λ4451, [O I] λλ6350, 6364, and a feature ascribed to Fe are traced to stimulate future modeling work. The uniqueness of SN 1998bw became less obvious once it entered the fully nebular phase (after 1 yr), when it was very similar to other Type Ib/c–IIb objects, such as the Type Ib SN 1996N and the Type IIb SN 1993J, even though SN 1998bw was 1.4 mag brighter than SN 1993J and 3 mag brighter than SN 1996N at a comparable phase. The late-phase optical photometry, which extends up to 403 days after B maximum, shows that the SN luminosity declined exponentially but substantially faster than the decay rate of $^{56}$Co. The ultraviolet-optical-infrared bolometric light curve, constructed using all available optical data and the early JHK photometry presented in this work, shows a slight flattening starting on about day +300. Since no clear evidence of ejecta-wind interaction was found in the late-time spectroscopy (see also the work of Sollerman and coworkers), this may be due to the contribution of the positrons since most γ-rays escape thermalization at this phase. A contribution from the superposed H II region cannot, however, be excluded.

Subject headings: gamma rays: bursts — supernovae: general — supernovae: individual (SN 1998bw)

1. INTRODUCTION

SN 1998bw was discovered by Galama et al. (1998b) in the BeppoSAX Wide-Field Camera error box of GRB 980425 (Soffita et al. 1998; Pian et al. 1999) close to a spiral arm of the barred galaxy ESO 184-G82, by comparing two frames taken at the ESO New Technology telescope (NTT) on April 28.4 and May 1.3 UT. Spectroscopic and photometric observations, both in the optical and in the near-IR, started at ESO—La Silla immediately after the discovery and showed that this object was profoundly different from all then known supernovae (SNe; Lidman et al. 1998). The peculiar spectrum led to diverse classifications. A few days after its detection, the object was classified as an SN Ib (Sadler et al. 1998) and later as a peculiar SN Ic (Patat & Piemonte 1998a; Filippenko 1998) owing to the complete absence of H lines, the weakness of the Si II λ6355 line, and no clear He i detection in the optical spectra.

Its peculiar spectroscopic appearance (Galama et al. 1998a; Iwamoto et al. 1998), its unusually high radio luminosity at early phases (Kulkarni et al. 1998), and, in particular, the probable association with GRB 980425 through positional and temporal coincidence (Galama et al. 1998a; Pian et al. 1999) placed SN 1998bw at the center of discussion concerning the nature of γ-ray bursts (GRBs; Wheeler 2001).

Independent photometric and spectroscopic data sets have been presented by several authors, whose results will be discussed and compared with those presented here...
throughout the paper. Here we give only a brief account of the main results of these previous works.

The early light curve of SN 1998bw has shown that the object was unusually bright when compared to known SNe of Type Ib/c ($M_r \sim -19.2 + 5 \log h_{\alpha};$ Galama et al. 1998a). The broadband photometric observations by McKenzie & Schaefer (1999) taken during the intermediate phases (47–171 days after maximum brightness) revealed that the object settled on an exponential decay similar to that observed in other Type Ic SNe. McKenzie & Schaefer first suggested that even in this case the light curve was powered by the radioactive decay of $^{56}\text{Co}$ with some leakage of $\gamma$-rays. Finally, the late-phase light curve was covered up to 500 days from the explosion by the observations of Sollerman et al. (2000). Their models achieved a fairly good reproduction of the data with the radioactive material well mixed in the ejecta and $M(\text{Ni}) \sim 0.5 \, M_\odot$.

The peculiar spectroscopic behavior of SN 1998bw around maximum light has been presented and discussed by Iwamoto et al. (1998), who identified the main spectral features as O I, Ca II, Si II, and Fe II. The estimated expansion velocities were exceptionally high ($\sim 30,000 \text{ km s}^{-1}$), and this caused a severe line blending. The evolution during the first months was unusually slow compared to known Type Ic SNe, with the nebular spectra still retaining many of the features present during the photospheric phase (Patat et al. 2000; Statidakis et al. 2000). The late onset of the fully nebular phase has been interpreted as an indication of a large ejected mass (Statidakis et al. 2000) since it was predicted by the early light-curve models (see below). During the intermediate phase, the emission lines were definitely broader than in known Type Ib/c supernovae, and the simultaneous presence of iron-peak and $\alpha$-elements indicated unusual relative abundances or physical conditions in the SN ejecta (Patat & Piemonte 1998b; Patat et al. 2000). The late spectroscopy presented by Sollerman et al. (2000) showed that the tentative morphological classification of SN 1998bw as a Type Ic event was indeed appropriate. The main features have been identified as [O I], Ca II, Mg I, and Na I D, the latter possibly contaminated by He I $\lambda 5876$.

Photometric and spectroscopic modeling of the early phases and the possible connection with GRB 980425 have been discussed by Galama et al. (1998a), Iwamoto et al. (1998), Höflich, Wheeler, & Wang (1999), Woosley, Eastman, & Schmidt (1999), and Pian et al. (1999).

The symmetric models of the early spectra and light curve by Iwamoto et al. (1998) and Woosley et al. (1999) reached a similar conclusion: SN 1998bw was generated by a core collapse with a large core mass of $0.5 \, M_\odot$. The required mass of $^{56}\text{Ni}$ is in this case 0.2 $M_\odot$. This low mass of radioactive material, however, seems too low to explain the late emission of the supernova (Sollerman et al. 2000).

In this paper we report on the results of an extensive observational campaign carried out at ESO–La Silla, which covered the evolution of SN 1998bw from the discovery until 417 days after the GRB detection. The paper is organized as follows: In § 2 we discuss the observations and reduction techniques for the optical and the near-IR. The evolution of SN 1998bw around maximum light is discussed in §§ 3, 4, and 5, which deal with low-resolution spectroscopy, polarimetry, and high-resolution spectroscopy, respectively. The He I detection in the near-IR spectra is presented in § 6, in which possible alternatives to the He I identification are also investigated. The description of SN 1998bw’s metamorphosis ends in § 7, where we follow its evolution into the nebular phase. The late-phase light curves are presented and compared with those of other SNe in § 8. This section also presents the ultraviolet-optical-infrared (UVOIR) bolometric light curve, which is compared to the model of Iwamoto et al. (1998). Finally, § 9 summarizes our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Optical Spectroscopy

Spectroscopic observations were obtained from early to late phases using the ESO 1.52 m (Boller and Chivens spectrograph), ESO-Danish 1.54 m (DFOSC), ESO 3.6 m (EFOSC2), and ESO-NTT (EMMI) telescopes. Exposure times ranged from 10 minutes near maximum light to several hours at late phases. The journal of spectroscopic observations is shown in Table 1.

The spectra were reduced using IRAF packages. For some of the spectra taken at the ESO-Danish telescope, it was not possible to remove the fringing in the red since suitable flat fields were not available. This gives rise to the high-frequency modulation of the spectra at wavelengths longer than 7500 $\text{Å}$.

Particular care was devoted to the extraction of the SN spectra to avoid contamination from the host galaxy background. Nevertheless, especially in the late-phase spectra, the contribution from an underlying H I region could not be completely eliminated, and thus unresolved narrow lines ($H_\alpha$, $H_\beta$, $[O I]$, $[O III]$) appear in the reduced spectra. We emphasize that these features do not show a coherent time evolution but rather depend on seeing conditions and slit position. For this reason we conclude that they are not intrinsic to the SN. Finally, there is no evidence of continuum contamination from the parent galaxy.

Wavelength calibration was achieved by using arc spectra from He-Ne-Ar lamps, while the response curves were obtained via observations of spectrophotometric standard stars (Oke 1990; Hamuy et al. 1992). The accuracy of the absolute flux calibration was finally checked against the broadband photometry and, when necessary, adjusted accordingly.

On 1998 May 6, two high-resolution spectra of SN 1998bw, covering the region 3750–7650 $\text{Å}$, were obtained at the ESO-NTT using EMMI in the echelle mode, with a 14 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
achieved.

\[ i.e., 50 \text{ km s}^{-1} \]

A ratio of about 15 in the region of the Na D doublet was estimated via plain aperture photometry, since at those early epochs the contribution from the host galaxy was negligible.

Near-IR photometry of SN 1998bw was obtained at three epochs with SofI at the ESO-NTT (see Table 2) through the \( J \), \( H \), and \( K \) passbands (Bessell & Brett 1988). In order to allow for a proper sky subtraction, the target was observed using the jittering technique. The reductions were performed in a standard way within IRAF, and the fluxes were estimated via plain aperture photometry, since at those early epochs the contribution from the host galaxy was negligible.

### TABLE 2

**IR Photometry of SN 1998bw**

<table>
<thead>
<tr>
<th>Date</th>
<th>JD</th>
<th>Phase*</th>
<th>( J )</th>
<th>( H )</th>
<th>( K )</th>
<th>Seeing</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998 May 18.3</td>
<td>50,951.8</td>
<td>+8</td>
<td>13.40 ± 0.04</td>
<td>13.35 ± 0.04</td>
<td>13.15 ± 0.04</td>
<td>0.7</td>
<td>NTT + SofI</td>
</tr>
<tr>
<td>1998 Jun 12.3</td>
<td>50,976.8</td>
<td>+33</td>
<td>14.41 ± 0.04</td>
<td>14.25 ± 0.04</td>
<td>14.20 ± 0.04</td>
<td>1.2</td>
<td>NTT + SofI</td>
</tr>
<tr>
<td>1998 Jun 30.3</td>
<td>50,994.8</td>
<td>+51</td>
<td>15.11 ± 0.04</td>
<td>14.98 ± 0.04</td>
<td>14.89 ± 0.04</td>
<td>0.9</td>
<td>NTT + SofI</td>
</tr>
</tbody>
</table>

* Relative to \( B \) maximum (JD = 2,450,943.8). This occurred 14.4 days after GRB 980425.
negligible. The photometric errors were estimated including the nightly zero-point variations, the aperture correction, and the photon shot noise.

Near-IR spectra of SN 1998bw were taken at the same epochs and with the same instrument used for the IR photometry. To cover the entire near-IR region, two grisms were used: one for the range 0.95–1.64 µm and one for the range 1.53–2.52 µm. The observations were made with the 1:0 slit. The resulting resolving power, measured from the comparison xenon spectrum, was λ/Δλ ~ 600 for both grisms.

As is standard procedure for IR spectroscopy, the SN was observed at two positions along the slit, and the telescope was nodded between these two positions once every few minutes. The highly variable night sky is then accurately removed by combining all spectra in the appropriate way. Atmospheric features have been removed by dividing the extracted spectra by the spectra of nearby bright stars that were observed soon after the SN: HD 135591 (May 18; Perryman et al. 1997), Hipparcos 106725 (June 6; Perryman et al. 1997), and BS 4620 and BS 6823 (June 30; McGregor Perryman et al. 1997), Hipparcos 106725 (June 6; Perryman et al. 1997), Hipparcos 106725 (June 6; Perryman et al. 1997), Hipparcos 106725 (June 6; Perryman et al. 1997), Hipparcos 106725 (June 6; Perryman et al. 1997). The stellar spectra often contain weak absorption lines from hydrogen (Paschen and Brackett series) and helium, which where removed before division. Wavelength calibration was achieved using comparison emission-line spectra of xenon gas lamps and is accurate to 1–2 Å. The spectra obtained with the two different grisms were then combined into a single spectrum.

Relative flux calibration was achieved by multiplying the spectrum by a blackbody curve with a temperature appropriate for the star used to remove the atmospheric features (HD 135591, T = 30,000 K; Hipparcos 106725, T = 5800 K; BS 4620, T = 13,000 K, and BS 6823, T = 25,000 K). Absolute flux calibration was performed by comparison to the broadband IR photometry at the same epochs.

2.3. Polarimetry

Spectropolarimetry of SN 1998bw was performed at two epochs (1998 May 4 and May 29) using the ESO 3.6 m telescope equipped with EFOSC2 in polarimetric mode (Patat 1999). A Wollaston prism was used with a focal plane mask to isolate the ordinary and extraordinary ray spectra of object and two sky positions; the separation of the two spectra is 20°. A half-wave plate was used to obtain spectra at four different position angles of 0°, 22°5, 45°, and 67°. The B300 grism was used, giving a resolution of 10 Å over the wavelength range 3400–7550 Å. Table 1 provides a journal of the observations. The air mass was large at the time of the observations, and the spectral region at λ < 4000 Å is severely affected by differential atmospheric refraction. The Hubble Space Telescope (HST) polarized standard star HD 161056 (Turnshek et al. 1990) was observed on each night to check the polarization and position angle calibration.

The data were bias subtracted, and the ordinary and extraordinary ray spectra of SN 1998bw were extracted with the local sky subtracted. Statistical errors were assigned to each extracted spectrum using the known properties of the detector (CCD ESO No. 40; Patat 1999). The data were then combined, following the procedure outlined by Tinbergen & Rutten (1992), and the total spectrum, linear polarization, and position angle were computed using dedicated programs running in the ESO MIDAS package (see Walsh 1992). The polarization was binned into equal wavelength bins to provide polarization errors per bin below 0.1% over the wavelength range 4000–7000 Å. For observations of HD 161056, the measured polarization in the V band was 4.3% at position angle (P.A.) 76°, in satisfactory agreement with the standard value of 4.04% at P.A. = 67°, given that Turnshek et al. (1990) suggest that it may be variable in polarization.

2.4. Optical Photometry

Late-time optical broadband photometry of SN 1998bw in the Johnson-Cousins UBVRI photometric system (Bessell 1990) was obtained in the phase range 310–403 days from B maximum. Table 3 shows the journal of the photometric observations, which were performed with the ESO-Dutch 0.9 m telescope, equipped with a TEK coated 512 × 512 pixel CCD (scale 0.44 pixel−1), and with the ESO 3.6 m telescope, equipped with EFOSC2 (Loral/Lesser 2048 × 2048 pixel CCD, scale 0.16 pixel−1). The SN is located on a spiral arm and superimposed on an H II region, which is clearly visible in Figure 1. At late phases the background contribution is significant, and the SN magnitude cannot be measured using plain aperture photometry. Therefore, after the standard bias and flat-field corrections, magnitude measurements were obtained by means of the point-spread function fitting technique implemented in SNOoPY (Patat 1996), a package specifically designed for SN photometry within the IRAF environment.

Color terms for the two instruments have been computed using observations of standard fields (Landolt 1992). The SN magnitudes have been calibrated by means of relative photometry with respect to the local sequence defined by P. M. Vreeswijk et al. (2001, in preparation; stars 1–10). The results of the late photometry here presented are in good agreement with those recently published by Sollerman et al. (2000).

<table>
<thead>
<tr>
<th>Date</th>
<th>JD (2,400,000 +)</th>
<th>Phase* (days)</th>
<th>U</th>
<th>B</th>
<th>V</th>
<th>R</th>
<th>I</th>
<th>Seeing (arcsec)</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 Mar 16.1</td>
<td>51,253.6</td>
<td>+310</td>
<td></td>
<td>20.69 ± 0.07</td>
<td>20.52 ± 0.07</td>
<td></td>
<td>...</td>
<td>1.3</td>
<td>Dutch 0.9 m</td>
</tr>
<tr>
<td>1999 Mar 17.1</td>
<td>51,254.6</td>
<td>+311</td>
<td></td>
<td>20.71 ± 0.07</td>
<td>20.50 ± 0.07</td>
<td>19.74 ± 0.05</td>
<td>...</td>
<td>1.3</td>
<td>Dutch 0.9 m</td>
</tr>
<tr>
<td>1999 Apr 8.1</td>
<td>51,276.6</td>
<td>+333</td>
<td></td>
<td>21.10 ± 0.15</td>
<td>20.69 ± 0.15</td>
<td>20.09 ± 0.15</td>
<td>...</td>
<td>1.1</td>
<td>ESO 3.6 m</td>
</tr>
<tr>
<td>1999 Apr 12.2</td>
<td>51,280.7</td>
<td>+337</td>
<td>21.13 ± 0.20</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>20.03 ± 0.15</td>
<td>1.1</td>
<td>ESO 3.6 m</td>
</tr>
<tr>
<td>1999 May 21.2</td>
<td>51,319.7</td>
<td>+376</td>
<td></td>
<td>21.59 ± 0.20</td>
<td>21.43 ± 0.20</td>
<td>20.83 ± 0.20</td>
<td>20.61 ± 0.20</td>
<td>1.2</td>
<td>ESO 3.6 m</td>
</tr>
<tr>
<td>1999 Jun 17.3</td>
<td>51,346.8</td>
<td>+403</td>
<td>21.69 ± 0.20</td>
<td>21.91 ± 0.20</td>
<td>21.70 ± 0.20</td>
<td>20.87 ± 0.20</td>
<td>20.76 ± 0.20</td>
<td>1.0</td>
<td>ESO 3.6 m</td>
</tr>
</tbody>
</table>

Notes.—Dutch 0.9 m = 0.92 m ESO-Dutch + CCD TK512, ESO 3.6 m = ESO 3.6 m + EFOSC2 + Loral/Lesser 2048.

* Relative to B maximum (JD = 2,450,943.8). This occurred 14.4 days after GRB 980425.
Fig. 1.—Upper panel: SN 1998bw in ESO 184-G82. The frame was obtained on 1999 June 17 (403 days after $B$ maximum light) in the $R$ band (5 minutes) with the ESO 3.6 m + EFOSC2. Lower panel: HST + STIS image of SN 1998bw environment at about 764 days after $B$ maximum light (Fynbo et al. 2000). The SN location is marked by a small circle, and the big circle centered on the SN position has a diameter of 1".
3. SPECTROSCOPIC EVOLUTION AROUND MAXIMUM LIGHT

The spectral behavior of SN 1998bw from day +7 to day +94 has already been discussed by Stathakis et al. (2000). The larger wavelength range and improved phase coverage of the data we are presenting here allow us to analyze the early phases in more detail and to push the discussion further into the late evolutionary stages. For a discussion of an independent late-phase data set, see Sollerman et al. (2000).

The spectroscopic evolution of SN 1998bw around maximum light is presented in Figure 2. Wavelengths are corrected to the parent galaxy rest frame, adopting $v_{\text{gal}} = 2532 \text{ km s}^{-1}$, as measured from the narrow Hα emission line (see § 5). Phases are from $B$ maximum, whose epoch (1998 May 10 UT) was estimated from the photometric data presented by Galama et al. (1998a). It occurred 14.4 days after the detection of GRB 980425. We adopt these conventions throughout the paper.

The general appearance of the spectrum at maximum light is quite unique among SNe, even though it is somewhat reminiscent of SN 1997ef (Filippenko 1997b; P. M. Garnavich et al. 2001, in preparation), which has been modeled as a massive SN Ic event (Iwamoto et al. 2000; Mazzali, Iwamoto, & Nomoto 2000). This appears clearly in Figure 3, where the spectrum of SN 1998bw is compared to those of other Type I SNe.

Another striking feature is the redward shift with time of most of the spectral features, both in absorption and in emission. At early phases the apparent broad emission-like features do not result from discrete emission lines but occur where absorption-line optical depths are low, and photons redshifting in the expanding ejecta, as a result of absorption and scattering processes, have a higher probability of escap-
In these early phases when the velocity is high, line blending is particularly severe. The modeling presented by Iwamoto et al. (1998) suggests that the main features are due to lines of Si II, O I, Ca II, and Fe II. The time evolution of the expansion velocity at the photosphere, as deduced from the minimum of the absorption trough of the Si II λ6355 line, is shown in Figure 5. For comparison, the corresponding values measured for the Type Ia SN 1994D, the Type Ic SN 1994I\(^{15}\), and the peculiar Type Ic SN 1997ef are also plotted. SN 1998bw shows a sudden break in the expansion velocity decline rate around day 15 and another at day 27. While changes in the slope are to be expected as a result of changes in optical depth at line center, the reasons for sudden changes are not clear. There is no doubt that the velocity decline rate changes significantly; what is less clear, in view of measurement uncertainties, is how suddenly they occurred.

The velocity deduced from the Si II λ6355 line is about 30,000 km s\(^{-1}\) at day \(-7\) and decreases to about 8000 km s\(^{-1}\) at day +22. These values are exceptionally high, for any SN, as can be seen in Figure 5. SN 1994I shows a trend that is very similar to that of SN 1998bw, although the velocities are systematically lower, while SN 1997ef deviates significantly after day 25 (Fig. 5). Phases for SN 1997ef are uncertain because maximum light was not recorded.

### 4. POLARIMETRY

In order to investigate any possible asphericity in the explosion of SN 1998bw, spectropolarimetry measurements were performed at two epochs (day \(-7\) and day \(+10\); see Table 1). The polarization averaged over the range 4000–7000 Å was 0.7% and 0.5% at the two epochs, respectively. Figure 6 shows the total spectrum (raw, not flux calibrated), the polarization binned into 200 channel bins, and the position angle of the polarization vector projected on the sky at both epochs. The formal errors per bin are about 0.04%, but the error on the polarization binned over the optical range is 0.1% given that the measurements were not of high photometric quality and the discrepancy on the measurement of the polarized standard. It appears that the polarization spectrum at day \(-7\) has a significant increase to the red that is not in evidence at the later epoch. In terms of the integrated polarization over the 4000–7000 Å range, there may be a marginal change in the polarization between the two epochs, but no great significance is attached to this result.

The interstellar polarization in the direction of the host galaxy can be estimated by the measurement of stellar polarization along a nearby sight line. Kay et al. (1998) measured the linear polarization of HD 184100 at 0.75% in P.A. Correcting the linear polarization results by this value of interstellar polarization results in 0.6% at P.A. 80° and 0.4% at 67° at days \(-7\) and \(+10\), respectively. The polarization value is not very different from the value of 0.53% measured by Kay et al. (1998) at day \(+42\) and is most probably intrinsic to the SN, although a dusty medium in the SN parent galaxy cannot be ruled out. However, the position angles differ from the Kay et al. value of 49°, although the errors on these earlier determinations are larger (at least 5°). Despite its association with a γ-ray burst, these polarization values are similar to those reported for other core-collapse SNe (Wang et al. 1996).

The small degree of polarization at optical wavelengths can be explained in terms of a moderate departure from sphericity (axial ratio less than 2:1; Höflich 1995; Höflich et al. 1999) either in the photosphere or in the outer scattering envelope when the line of sight is not coincident with...
an axis of symmetry. Unfortunately, it is not possible from polarization measurements alone to decode both the shape of the object and the viewing angle, and therefore the small polarization values reported here could indicate large departures from sphericity but viewed close to an axis of symmetry or small departures viewed well away from the symmetry axis. Net polarization could also result from a spherical envelope in which, as a result of large-scale clumping, one hemisphere had a surface brightness different from that of the other hemisphere. Delayed light echoes could also be responsible for the observed polarization, provided that the time delay is comparable to the timescale of the SN luminosity variation.

We note that no polarization, either circular or linear, was detected in the radio, and this has been interpreted as the signature of a spherically symmetric blast wave (Kulkarni et al. 1998). This apparent discrepancy might suggest that the radio and the optical radiation were generated in regions of different geometry.

5. HIGH-RESOLUTION SPECTROSCOPY

To search for possible narrow emission lines produced in the circumstellar environment of the progenitor and for interstellar absorption features, we obtained high-resolution spectra of SN 1998bw around maximum brightness. With the exception of a narrow Hα emission line centered at 2532 km s⁻¹ and probably arising from the underlying H II region (see also § 2.1 and Tinney, Stathakis, & Cannon 1998), neither the usual Na I D absorption lines, which would signal intervening interstellar dust, nor narrow emission lines were detected. However, the signal-to-noise ratio we achieved (SNR ~ 20 at Hα and ~15 at Na I D) is insufficient to exclude the presence of lines, both in emission and absorption, with EW ≤ 0.2 Å. Using the relation recently calibrated by S. Benetti, E. Cappellano, P. Mazzali, F. Patat, & M. Turatto (2001, in preparation) and assuming that the total EW of the Na I D doublet is EW ≤ 0.4 Å, one can estimate an upper limit for the extinction, A_V ≤ 0.2. There are two values of A_V available in the literature, i.e., A_V = 0.05 (Burstein & Heiles 1982) and A_V = 0.2 (Schlegel, Finkbeiner, & Davis 1998). Both estimates are compatible with our upper limit, but we will assume A_V = 0.2 throughout this paper due to its more recent determination from COBE/DIRBE maps and the IRAS Infrared Sky Survey Atlas.

6. INFRARED SPECTRA: HELIUM AND OTHER ELEMENTS

The IR spectra are plotted in Figure 7. The most prominent feature is the broad emission at 1.08 μm, which has an associated P Cygni structure with a hint of more than one component in absorption. The main component of the emission and the absorption minimum at day +8 strongly suggest that this feature is due to He I 1.083 μm with a velocity of 18,300 ± 700 km s⁻¹. There is nevertheless the possibility that transitions from other ions are affecting this profile. The absorption does not seem to shift redward with time as shown in the upper panel of Figure 8. This is to be expected if the helium were confined to an outer higher velocity layer either optically thick or thin but restricted to a narrow velocity range. A more extended layer that had become optically thin on or before the date of the first IR spectrum could also in principle give rise to this constancy of velocity. The first interpretation is reinforced by the fact that at the same phase (i.e., 22.4 days after the explosion),
of He I, one may conclude that excitation is caused by nonthermal electrons produced by $\gamma$-rays coming from the radioactive decay of $^{56}$Co. This was predicted by Chugai (1987) for SN 1987A and shown to be effective by Graham (1988), Lucy (1991), and Mazzali & Lucy (1998) in various SNe, after Harkness et al. (1987) had identified He I lines by postulating large departures from LTE to explain the abnormal strengths.

He I has another transition (singlet series) in the near-IR, namely, at $2.058 \mu$m (2$^1$$S$–2$^1$$P$). Careful inspection shows that in all three spectra a weak broad P Cygni feature is present at this wavelength (see Fig. 7). While this confirms the presence of He I in the spectra, because this spectral region is affected by strong telluric absorption, any line strength measurements should be treated with some caution. In the lower panel of Figure 8 the region centered on 2.058 $\mu$m is plotted for day +51, i.e., when this feature appears to be more pronounced. Even though the signal-to-noise ratio is poor, a P Cygni profile is visible and from the minimum of the absorption through an expansion velocity of $13,000 \pm 2000$ km s$^{-1}$ is deduced, while the measured intensity ratio $R(2.058) = 30$.

Since these He I lines show P Cygni profiles associated with strong continuum radiation, it is instructive to follow the qualitative results obtained by an elementary SN model in the Sobolev approximation (see, for example, Jeffery & Branch 1990). In that framework, the absolute emission line intensity not only depends on the line optical depth but also is proportional to the photospheric continuum intensity at the line wavelength. Thus, it is not surprising that the emission component of He I 1.083 $\mu$m is much greater than that of He I 2.058 $\mu$m. There is in fact roughly a factor 10 difference in the continuum flux at the two wavelengths, and therefore the measured intensity ratio translates into an equivalent width ratio $EW(He I 1.083)/EW(He I 2.058) \sim 3$. The theoretical work by Lucy (1991) on the nonthermal excitation of helium in Type Ib SNe predicts a ratio close to 1 for these two He I features, whereas the ratio between the $A$-values is 5.2 (Martin 1987).

An additional complicating aspect to consider is that the He I 1.083 $\mu$m line originates from the metastable triplet ground state, which can give rise to resonance scattering not expected for the He I 2.058 $\mu$m line, whose lower level is metastable but whose upper level can be depopulated by an allowed transition to the singlet ground state. Moreover, the intensities of the two lines depend also on the fraction $\epsilon$ of collisional to total depopulations of the upper level of the transition. Hence, if one takes also into account that the optical depths of the two lines can be different, it is not surprising that the observed line ratio deviates from the expectations based on Einstein coefficients alone.

We note that the IR spectra of SN 1987A have shown a strong He I 1.083 $\mu$m line starting at day 110 (Meikle et al. 1989), from which an expansion velocity of 5000 km s$^{-1}$ was deduced. The He I 2.058 $\mu$m line was also detected with an expansion velocity of 1500 km s$^{-1}$. Meikle et al. (1989) suggested that this is probably due to the fact that He I 2.058 $\mu$m was optically thin. For SN 1987A, the ratio He I 1.083/He I 2.058 in the phase range 110–349 days ranged from 23 to 50. In particular, on day 112 it was about 35; once one has taken into account the different continuum levels at the two wavelengths, this turns into an equivalent width ratio of about 6.

Very few other SNe have been observed in the 2 $\mu$m region. The Type II SN 1995ad and Type Ic SN 1997B have both shown a strong He I 1.083 $\mu$m feature without any evidence of the He I 2.058 $\mu$m line (Clocchiatti et al. 2001). He I 1.083 $\mu$m was identified also in the near-IR spectra of the Type IIb SN 1998S (Gerardy et al. 2000), and in that case, even though very faint, the He I 2.058 $\mu$m line was detected at 95 days after $V$ maximum.

One possible difficulty with the identification of the 1.083 $\mu$m feature as He I comes from the apparent absence of the He I lines in the optical spectra at comparable phases. In Figure 9 we plot the optical spectra at days +6, +29, and +52, i.e., as close in time as possible to the IR spectra. At all three epochs, the spectrum is predominantly an absorption spectrum. Some of the strongest features tentatively identified using spectral synthesis are marked (top). We also marked the expected position of the He I absorption lines if they all had a blueshift of 18,300 km s$^{-1}$ (bottom). The strongest optical line of He I should be $\lambda 5876$, but this is blended with Na I D. He I $\lambda 5876$ is clearly not present as a distinct individual feature at 18,300 km s$^{-1}$. There is no unambiguous sign of any other possible He I optical lines. This does not necessarily contradict the identification of the 1.083 $\mu$m feature as He I, because the optical lines can be suppressed relative to the IR ones if nonthermal excitation is at work (Mazzali & Lucy 1998). The large expansion velocity of SN 1998bw might also dictate greater blending effects in the optical region where the number of lines per unit wavelength is much larger than in the IR.

The optical He I lines are at least weaker than in the Type Ic SN 1994I. This SN also showed the He I 1.083 $\mu$m line (Filippenko et al. 1995) and possibly traces of He I contamination in the optical (Clocchiatti et al. 1996). Millard et al. (1999) have modeled SN 1994I’s spectra and could fit the feature near 1.08 $\mu$m using a blend of C I 1.0695 $\mu$m and He I 1.083 $\mu$m, the latter being detached at 18,000 km s$^{-1}$. This
velocity is similar to what is seen in SN 1998bw. However, they were able to obtain an alternative fit using only Si I lines. Another possibility is that the feature at 1.08 μm is due to Mg II 1.091 μm, as suggested by Mazzali & Lucy (1998) for the Type Ia SN 1994D.

Determining the amount of He in the ejecta is very important for constraining the nature of the progenitor and its evolutionary stage at the time of the explosion. Detailed spectral modeling, including nonthermal effects, is necessary for this purpose. Inclusion of helium in the exploding progenitor object may even affect our quantitative conclusions concerning the ejected mass, mass of radioactive material, kinetic energy, and mixing of the ejecta.

As the SN ages, the 1.083 μm emission feature develops a second, redder component (see Fig. 7). Possible identifications are O I 1.129 μm and Na I 1.138, 1.140 μm. The latter seems to be possible since its lower level is the upper level of the Na I D line transition, which would be well populated by resonance scattering. The Na I identification implies a velocity close to that of Si II λ6355 at the same phase and consistent with the Na I D line absorption. The presence of O I λ7771 in the optical is only a weak argument in favor of the O I 1.129 μm identification, since this latter line originates from a higher level.

7. ENTERING THE NEBULAR PHASE

The spectral evolution of SN 1998bw toward and during the nebular phase is presented in Figure 10, which shows all our spectra taken between day +29 and day +376. The transition from an absorption to an emission spectrum is slow and subtle and is marked by a decrease in the continuum.

While the evolution of SN 1998bw in the range 5500–9000 Å is similar to that of SN Ic events such as SN 1987M (Filippenko, Porter, & Sargent 1990), the expansion velocities are larger, and the region between 4000 and 5500 Å is dominated (at least until about day +200) by a wide bump to which Fe II transitions probably contribute significantly. The spectroscopic differences appear clearly in Figure 11, where SN 1998bw is compared to the Type Ia SN 1992A, the Type Ib SN 1996N, and the Type Ic SN 1996aq. From Figure 11 the late nebular spectrum of SN 1998bw appears to mostly resemble a Type Ic SN, in this case SN 1996aq. Mg II λ4571 and [O I] λ6300 are present in both cases but not in the Type Ia SN 1992A. SNe Ia in general show strong [Fe II] and [Fe III] emission features not apparent in the same form in the two Type Ic SNe. In fact, the strongest spectral resemblance of SN 1998bw at nebular phases is to the peculiar SN 1985F and the Type Ic SN 1987M (Filippenko et al. 1990). Qualitatively, the appearance of Mg I and O I is consistent with what is expected from the nucleosynthesis model of Iwamoto et al. (1998) and their absence in models of Type Ia proposed by Nomoto et al. (1997).

All these facts support the general idea that SN 1998bw is related to SNe Ib/c. It might be regarded as an extreme case among these objects, having large kinetic energy, ejecta mass, and ejected mass of synthesized 56Ni, while SN 1997ef could represent a less extreme case closer in properties to the known SNe Ic (see also Iwamoto et al. 2000; Mazzali et al. 2000; Statidakis et al. 2000; Branch 2001).

At late epochs the most prominent spectral feature is the [O I] λ6300, 6364 doublet. Figure 12 (upper and middle panels) reveals that this line has a complex profile, showing an apparently blended emission component blueshifted by approximately 2300 km s⁻¹ with respect to the λ6300 doublet component. It is present at 201 and 376 days, and a similar feature appears to be present in the spectra of SN

![Fig. 10.—Spectroscopic evolution of SN 1998bw from day +29 to day +376. The phases have been computed from B maximum light (1998 May 10). For presentation the spectra have been vertically shifted by arbitrary amounts: +45′ (−0.20), +52′ (−0.55), +64′ (−0.95), +73′ (−1.20), +94′ (−1.50), +125′ (−1.70), +201′ (−1.90), +337′ (−2.00), and +376′ (−2.70). Narrow emission lines visible in the late-time spectra originate in the parent galaxy. Spectra are in the host galaxy rest frame.](image)

![Fig. 11.—Comparison between SNe 1992A (Ia; ESO-KP database), 1998bw, 1996N (Ib; Sollerman et al. 1998), and 1996aq (Ic; ESO-KP database, unpublished) at late phases. The vertical dashed line is placed at the rest-frame wavelength of Mg I λ4571.](image)
of SNe of similar type is interesting. The FWHM of Mg I $\lambda 4571$ in the latest spectra of the Type Ib SN 1983N (225 days; Gaskell et al. 1986) and the Type Ic SN 1996aq (270 days) was about $5000 \pm 300$ and $7000 \pm 800$ km s$^{-1}$, respectively. A similar value ($6100$ km s$^{-1}$) was reported by Sollerman, Leibundgut, & Spyromilio (1998) for the Type Ib SN 1996N at about 220 days. These values are to be compared with $9800 \pm 500$ km s$^{-1}$ measured for the same line in SN 1998bw at 201 days past maximum. However, this value reduces to $7700 \pm 800$ km s$^{-1}$ if we determine the velocity using only the red half of the profile. Thus, it seems that when account is taken of the somewhat different phases at which measurements were made for these SNe, not very significant differences are noticeable.

A similar analysis is more complicated for the [O I] doublet, because of both its complex profile (see Fig. 12) and a strong contamination by the Si II $\lambda 6355$ line on the red wing at phases earlier than 3 months (see Fig. 13, left panel). We tried to estimate the expansion velocity of the O I nebula using the blue wing of the observed profile and hence computing the FWHM of the $\lambda 6300$ component alone. The results are plotted in the upper panel of Figure 14, which shows that the velocities are similar to those computed from Mg I.

Finally, we have measured the flux of the Mg I and [O I] lines to look for possible deviations from exponential decay. The results are plotted in the lower panel of Figure 14, where it appears clearly that at late phases the flux in these lines decreases exponentially. The measured decline rates are 0.0185 and 0.0170 mag day$^{-1}$ for the two features, respectively. These values are quite similar to those measured for the broadband photometry (see § 8). It should be noted here that Si II $\lambda 6355$ line emission probably dominates the [O I] $\lambda 6300$, 6364 lines up to day 94, although there is the possibility that if [O I] is optically thick and the expansion velocities significantly exceed the doublet separation, most of the [O I] photons would be redshifted and confused with those belonging to the Si II $\lambda 6355$ transition.

The unidentified blueshifted component of Mg I will clearly dominate the photometry of this feature prior to day 125 and still contribute afterwards. The fact that Mg I appears to reach the exponential decay line before [O I] (see Fig. 14, lower panel) could be due to the nature of these blending effects. Also, other considerations may be important, such as the fact that the critical density for Mg I is 3 orders of magnitude higher than that for [O I] and the expanding envelope results in the former critical density being reached well before the latter. Also, since Mg I has a much lower ionization energy than O I, emission of these different lines may be coming from different regions. Finally, models of massive stars (Woosley, Langer, & Weaver 1995) show that magnesium occupies a more con-

![Fig. 12.—Upper and middle panels: The [O I] $\lambda \lambda 6300, 6364$ line profile at two different epochs for SN 1998bw (thick line) and SN 1996N (thin line; Sollerman et al. 1998). The vertical dotted line is placed at the position of the unidentified feature (see text). Velocities are computed from the $\lambda 6300$ doublet component. Lower panel: Comparison between the profiles of [O I] $\lambda \lambda 6300, 6364$ (thick line) and Mg I $\lambda 4571$ (thin line) for SN 1998bw at $+376$ days.](image)
fig. 13.—Evolution of Mg I λ4571 (right panel) and [O I] λλ6300, 6364 (left panel) line profiles.

Refined radial distribution than oxygen. This is the case not only for extremely massive stars but also for 13–15 $M_\odot$ stars (see Fig. 1 of Nomoto, Iwamoto, & Suzuki 1995). In both circumstances, the region where O exists without Mg is mostly He rich, the He mass fraction being ~0.1.

Unfortunately, it is not possible to make a similar analysis for the presumed Fe lines and particularly the feature near 5215 Å. In fact, even the identification of this feature is in doubt. One promising possibility is that it is due to the [Fe II] multiplet 19 with additional components due to the [Fe II] multiplets 16, 17, and 18. The [Fe II] multiplet 6 may then contribute to the blend near Mg I λ4571. Nevertheless, there is no unequivocal evidence for the presence of other multiplets of [Fe II]. Another possibility suggested by Filippenko et al. (1990) for SN 1985F and SN 1987M is a combination of Fe II multiplets 35, 42, and 49. Contributions from [Fe III] multiplet 1 seems a more remote possibility because some important lines are not present. What we can state here is that the most prominent feature, the one at 5215 Å, declines faster than those of Mg I and [O I]. The flux measurement is strongly hampered by the uncertain position of the continuum and the possible presence of another feature in the red wing (see Fig. 10). To reduce the effect of these problems, we computed the fluxes by integrating the spectra in the range 5080–5680 Å and crudely assuming the continuum level. To estimate the uncertainty involved, we chose the continuum at two extreme positions. One is the average value in the range 5680–5700 Å, where the flux drops to a minimum value, and the other is the level used in computing the flux of the Mg I λ4571 measurements.

The results are shown in the lower panel of Figure 14, where the upper and lower extremes of the error bars represent the values obtained using the low and high continua, respectively. The conclusion is that the λ5215 feature fades at a rate of $0.021 \pm 0.001$ mag day$^{-1}$, i.e., $0.0025 \pm 0.001$ and $0.004 \pm 0.001$ mag day$^{-1}$ faster than [O I] and Mg I, respectively. The faster decline of λ5215 is also clearly visible, if one compares its intensity to the one of the adjacent Mg I λ4571 after normalization to its peak (see Fig. 15). This fact might also suggest that the λ5215 feature does not trace the bulk of the Fe in the envelope since one would expect the abundance of Fe to be increasing with time as a result of the radioactive decay of $^{56}$Co. This might be partially compensated by the decreasing temperature and density of the ejecta.
Another point concerns the expansion velocity deduced from this feature. Again the measured values are quite uncertain, but at day 201 the FWHM velocity is about 10,900 km s$^{-1}$ and hence higher than those estimated for Mg I $\lambda$4571 (9800 km s$^{-1}$) and [O I] $\lambda\lambda$6300, 6364 (7600 km s$^{-1}$). However, if the $\lambda$5215 feature results from a blend of multiplet lines of whichever type, this would most certainly lead to an overestimate of the expansion velocity since the separation of individual lines of the most likely multiplets is of the order of thousands of kilometers per second. Here we only note that recent Chandra X-ray observations of Cas A, which is consistent with the remnant of a massive star explosion (e.g., Fesen, Becker, & Blair 1987), show that significant amounts of Fe are present at high velocities, comparable to those of lighter elements such as oxygen (Hughes et al. 2000). This implies that a relevant fraction of the material synthesized in the core has mixed into the outer regions during the SN explosion.

Finally, we have compared SN 1998bw with the Type IIb SN 1993J and the Type Ib SN 1996N at about 1 yr after maximum light (Fig. 16). The resemblance of the three objects is evident. In particular, SN 1993J and SN 1998bw are strikingly similar, the only deviation being the broad Hα, which is missing in SN 1998bw; apart from this, line ratios and expansion velocities are definitely comparable. SN 1996N also has very similar line widths, while the luminosity ratio between [O I] and all other features is smaller and the blue [Fe II] bump is less pronounced.

Despite the great peculiarity shown in the early phases, at 1 yr after maximum SN 1998bw is spectroscopically indistinguishable from known Type Ib SNe. Even the high expansion velocities measured during the first 6 months have slowed down to the values that are typical for other Type Ib SNe ($\sim 5000$ km s$^{-1}$). But, the much higher ejected mass estimated by the models and the high luminosity, which persists also at these advanced phases (see next section), confirm that this event was hyperenergetic.

8. BROADBAND AND BOLOMETRIC LIGHT CURVES

The photometric data presented in this paper and those published by Galama et al. (1998a), McKenzie & Schaefer (1999), and Sollerman et al. (2000) can be collected in a
unique data set to study the late-phase behavior of the light curves, as shown in Figure 17. This figure shows that the SN luminosity follows an exponential luminosity decline up to about 300 days after maximum light, while a clear flattening is present for the latest observed epochs, especially in the V band. This is clearly shown in Table 4, where we have reported the decay rates computed via linear least-squares fit to the data in the two phase ranges 40–330 and 300–490 days from B maximum. The values for the earliest data are consistent, within the estimated errors, with those computed by McKenzie & Schaefer (1999) using data in the range 47–171 days (γ_B = 0.0141 ± 0.0002, γ_V = 0.0184 ± 0.0002, and γ_I = 0.0181 ± 0.0002 mag day^{-1}). In any case, these slopes deviate clearly from the values expected from the ^56Co → ^56Fe radioactive decay in the case of complete γ-ray trapping (0.0098 mag day^{-1}), as already noticed by McKenzie & Schaefer (1999). On the other hand, the measured slopes are similar to those reported by Sollerman et al. (1998) for the Type Ib SN 1996N in the phase range 180–340 days (γ_B = 0.0167 ± 0.0023, γ_R = 0.0172 ± 0.0010, and γ_I = 0.0193 ± 0.0024 mag day^{-1}). These values are even higher than those typical for the late-phase data of Type Ia SNe. If ^56Co decay is powering the late light curve of SN 1998bw, there must be a fairly strong leakage in the γ-ray deposition, as for SN 1996N (Sollerman et al. 1998). Interestingly, fast and slow decliners seem to exist within the Type Ic class, as pointed out by Clocchiatti & Wheeler (1997). The range spanned by late-phase decline rates of SNe Ib/c is quite broad: γ ranges from 0.006 (SN 1990B; Piemonte 2001) to 0.022 mag day^{-1} (SN 1990I; ESO-KP database). At later phases (t ≥ 300 days), a clear flattening of the light curve is visible in all passbands, even though the conclusion about B band is somewhat hampered by the lack of data at phases later than 403 days. The decline rate variation is 0.0020 ± 0.0013, 0.0079 ± 0.0010, 0.0036 ± 0.0020, and 0.0043 ± 0.0013 mag day^{-1} in B, V, R, and I, respectively.

In Figure 18, we present the UVOIR bolometric light curve of SN 1998bw, which was constructed using all available data by integrating the flux in the optical and near-IR photometric bands. Magnitudes were converted to fluxes using the calibrations of Bessell (1979) and Wilson et al. (1972). The measured fluxes were then transformed to luminosities by adopting a distance modulus μ = 32.89 (d = 37.8 Mpc; H_o = 65 km s^{-1} Mpc^{-1}) and an extinction A_V = 0.2. We emphasize that JHK photometry is available only for the early phases and that its contribution to the total flux is quite significant, ranging from ~25% on day 22.4 (from GRB) to ~35% on day 65.4. For later epochs we simply assume that the fractional IR contribution remained constant at 35% as for the last measurement. Clearly, this is a major source of uncertainty for the late UVOIR bolometric light curve.

After the maximum peak, where the SN reaches a luminosity of ~10^{43} ergs s^{-1}, the light curve settles on the exponential decay tail starting with day +40, with a decline rate γ = 0.0176 ± 0.0002 mag day^{-1}. Then, after day +300, the bolometric light curve appears to flatten, gradually deviating from the slope defined by the data in the range 40–200 days (dotted line), so that at +490 days the difference is about 1.4 mag, which is well outside the error bars (see Fig. 18). These uncertainties were estimated taking into account the presence of possible contamination from the unresolved underlying H II region, whose contribution is difficult to subtract (see below).

The comparison of the bolometric light curve of SN 1998bw with the model of Iwamoto et al. (1998) is also

![Figure 17. BVRI broadband light curves of SN 1998bw at t > 40 days. For presentation the light curves have been shifted by the reported amounts. No extinction correction has been applied. The dotted and dashed lines represent least-squares fittings to the data in the ranges 40–330 and 300–490 days past B maximum. Data are from Galama et al. (1998a), McKenzie & Schaefer (1999), Sollerman et al. (2000), and this work. The thick dashed line corresponds to the ^56Co → ^56Fe decay rate, expected for full γ-ray trapping. Epochs refer to the B maximum light.](image)

### Table 4

<table>
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<th>B</th>
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<th>R</th>
<th>I</th>
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<td>40.8–325.6</td>
<td>40.8–325.6</td>
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<td>311.6–489.6</td>
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<tr>
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<td>0.0101 ± 0.0008</td>
<td>0.0129 ± 0.0006</td>
<td>0.0126 ± 0.0008</td>
</tr>
</tbody>
</table>

*Relative to B maximum (JD = 2,450,943.8).*
presented in Figure 18. Although the early phases ($t \lesssim 60$ days) are well reproduced, the observed tail deviates from the theoretical prediction. The model must be highly energetic to accommodate the early light curve and spectra. Therefore, at later phases $\gamma$-rays should escape quite efficiently, resulting in a rapid decline. Eventually, most $\gamma$-rays escape from the ejecta, and only positrons from the $^{56}$Co decay contribute to the light curve (the masses of $^{56}$Co and $^{44}$Ti in the model are small). Indeed, after day $\sim 200$ the calculated decline becomes slower, and it approaches the decay rate of $^{56}$Co around day 400 (Iwamoto et al. 1998; Nakamura et al. 1999, 2000, 2001).

Nomoto et al. (2001) and Nakamura et al. (2001) have shown that, while the highly energetic model can explain the early light curve, a less energetic model is in better agreement with the late light curve. They suggest that such a behavior reflects some nonspherical effects in the ejecta structure, although the well-mixed models of Sollerman et al. (2000) do not require asymmetries for a reasonable match to the light curves and neither do those of Chugai (2000).

Jeffery's (1999) ad hoc model, although based on a rather different model of the ejecta, also predicts that the pure exponential phase should end after about day 400 and that the light curve should slowly approach the $^{56}$Co decay slope when eventually only the positrons are deposited (provided that other, less abundant radioactive species remain unimportant and interaction with circumstellar material does not occur). In this respect it is interesting to note that a least-squares fit to the bolometric light curve in the phase range 376–490 days gives a slope $\gamma = 0.009 \pm 0.001$ mag day$^{-1}$, which would suggest that SN 1998bw finally settled on the $^{56}$Co decay. Nevertheless, a possible alternative is that the flattening is due to the unaccounted presence of other sources within the ground-based point-spread function. In order to reproduce the observed behavior, the integrated magnitude of the contaminating objects must be $V \sim 22.6$. Even though recent HST Space Telescope Imaging Spectrograph (STIS) observations (Fynbo et al. 2000) have shown that several objects are present within a radius of 0:5 from the SN location (Fig. 1), there is no evidence for such a relatively bright source. Hence, the conclusion is that the observed flattening is, at least to some extent, intrinsic. However, this can only be confirmed by follow-up observations by HST. On the other hand, the effects of possible freeze-out, ejecta-wind interaction, or even faint echoes should not be overlooked.

As a matter of fact, no signs of ejecta-wind interaction are found in the late-phase spectra of SN 1998bw (see also Sollerman et al. 2000). Nevertheless, some circumstellar material (CSM) is expected to be present. All models for SNe Ic assume that the progenitor stars undergo intense mass loss and lose their H-He envelopes to become bare CO cores before they explode. Thus, interaction should be expected at some stage. Future observations will be fundamental to investigate the circumstellar environment and the real onset of ejecta-wind interaction.

In Figure 19 the absolute $V$ light curve of SN 1998bw is presented and compared with the light curves of some Type II (1987A, 1979C), IIb (1993J), Ia (1991T, 1992A), Ib (1990I), and Ic (1992ar, 1994I) SNe. For SN 1998bw, a distance...
modulus $\mu = 32.89$, while the interstellar extinction is assumed to be $A_V = 0.2$ mag (see § 5). It is clear that the light curve alone would not allow one to classify this object as an SN Ib/c nor, indeed, to distinguish it from thermonuclear SNe.

Even though the internal extinction for SN 1994I is very uncertain (here we adopted $A_V = 1.2$), SN 1998bw was much brighter and had a different light curve shape. Unfortunately, late-phase data for SN 1994I are not available. However, a comparison is possible with the Type Ib SN 1990I. Maximum light was not covered by the observations, but the light curve of SN 1990I between day +40 and day +120 is very similar to that of SN 1998bw, although about 0.5 mag fainter. After that, the luminosity decay rate of SN 1990I was larger than that of SN 1998bw. Later on, the overluminosity of this SN becomes more pronounced. At 350 days the Type Ib SN 1993J is 1.4 mag fainter then SN 1998bw (see Fig. 19). SN 1996N is even less luminous as shown by Sollerman et al. (1998), even though the distance modulus, reddening, and epoch of maximum are rather uncertain. One year after the explosion, this SN is about 3 mag fainter than SN 1998bw.

As discussed before, we believe the late-time light curve of SN 1998bw is powered by the radioactive decay of $^{56}\text{Co}$ into $^{56}\text{Fe}$ and therefore the late luminosity can be used to constrain the $^{56}\text{Ni}$ mass ejected by the explosion. The decay of $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ releases energy through the $\gamma$-ray channel in 81% of the cases, while the remaining fraction goes into positrons, which annihilate with electrons producing $\gamma$-rays (see Colgate & McKee 1969). The positron kinetic energy released before the annihilation accounts for 3.5% of the total $^{56}\text{Co}$ decay energy (Arnett 1979; Woosley, Pinto, & Hartmann 1989).

In the case of SN 1998bw, since the slope of the late light curve prior to 300 days is steeper than the expected input energy from $^{56}\text{Co}$ decay, we can assume that in this phase range some fraction of the $\gamma$-rays escapes thermalization. At later epochs ($t > 400$ days), the envelope becomes completely transparent to $\gamma$-rays, whereupon in the case of complete deposition of positron kinetic energy (Axelrod 1980), the late light curve settles on the $^{56}\text{Co}$ decay line.

Making the crude assumption that the phase of complete escape of $\gamma$-rays and complete deposition of positrons was reached after 400 days and assuming a rate of $^{56}\text{Co}$ decay energy production of $s = 6.78 \times 10^9$ erg s$^{-1}$ (Sutherland & Wheeler 1984) and a half-life time of 77.12 days (Arnett 1996, p. 428), we can estimate the mass of $M^{^{56}\text{Ni}}$ using the following equation:

$$M^{^{56}\text{Ni}} \leq \frac{L_{43}(t)}{1.35e^{-\tau_{111.26}} \times 0.35} M_\odot,$$

(1)

where $L_{43}(t)$ is the bolometric luminosity in $10^{43}$ erg s$^{-1}$, $t$ is expressed in days from the explosion, and the factor 0.35 is the fraction of total $^{56}\text{Co}$ decay energy deposited by positrons. If we use the four available measurements at $t > 400$ days (Sollerman et al. 2000; this work) and average the results, we get $M^{^{56}\text{Ni}} \leq 1.0^{+0.5}_{-0.2} M_\odot$. The errors are by far dominated by the uncertainties in the bolometric luminosities, and the estimate depends on our assumption on the IR contribution at these late phases.

We note that the model by Nakamura et al. (2001) estimated the mass of $^{56}\text{Ni}$ to be $0.4 M_\odot$ from the early light curve modeling. This value is not in contradiction with what is found here if the SN envelope is not completely transparent to $\gamma$-rays at $t > 400$ days. Moreover, it must be noted that Nakamura et al. (2001) have suggested that positron contribution is not yet dominant in powering the light curve at the phases covered by the last available observations.

9. DISCUSSION AND CONCLUSIONS

As we have shown, SN 1998bw was exceptional in many respects, even beyond its possible and probable connection with GRB 980425. The luminosity at maximum was comparable to that of an SN Ia, but its spectral appearance was completely different from that of other Type Ib/c events. This gives qualitative support to the idea that the material ejected by SN 1998bw was rich in both Fe-peak and $\alpha$-elements. The possibly large production of Fe-peak elements makes it important to obtain detailed nucleosynthesis calculations and rate estimates of the occurrence of such objects, because they might have a significant impact on models of galactic chemical evolution. Since SN 1998bw was as bright as an SN Ia, it might seem
unlikely that such objects would be missed in nearby searches. Nevertheless, SN 1998bw may have been missed had there not been an associated GRB. Does this allow us to infer that such kinds of explosions must be intrinsically rare at the present epoch?

But, even if they are relatively rare now, their past frequency may have been considerably higher. SN 1998bw is thought to have been generated by a massive star (see Iwamoto et al. 1998; Woosley et al. 1999), which may have been more common at remote epochs, when the rate of star formation was higher. Since the timescale for the release of iron and oxygen into the interstellar medium by these objects is much shorter than for SNe Ia and significantly less massive core-collapse SNe, hypernovae may have played an important role in the initial galactic chemical enrichment. Future work will concentrate on establishing whether the rate of occurrence of such SNe increases with redshift or look-back time. It is possible that the discovery of many GRBs at significant redshift is already a hint in this direction, as is the conclusion for several of them that the light curve can be reproduced with a combination of a GRB afterglow plus an SN light curve (see Bloom et al. 1999).

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