SN 1998BW AT LATE PHASES
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ABSTRACT
We present observations of the peculiar supernova SN 1998bw, which was probably associated with GRB 980425. The photometric and spectroscopic evolution is monitored up to 500 days past explosion. We also present modeling based on spherically symmetric, massive progenitor models and very energetic explosions. The models allow line identification and clearly show the importance of mixing. From the late light curves, we estimate that \( \sim 0.3 - 0.9 \ M_\odot \) of ejected \(^{56}\text{Ni}\) is required to power the supernova.

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

1. INTRODUCTION

SN 1998bw was born famous because of its positional and temporal coincidence with GRB 980425 (Galama et al. 1998). The unique nature of the associated radio source, in terms of the high luminosity immediately after the explosion and the inferred relativistic expansion rate (Kulkarni et al. 1998), argues that SN 1998bw and GRB 980425 are related. Independent of the connection to the gamma-ray burst, SN 1998bw is an interesting supernova. It was optically luminous and displayed very high expansion velocities. SN 1998bw was classified as a Type Ic supernova (Patat & Piemonte 1998), and late-time spectra reported here are consistent with this classification.

Modeling of the early light curve and spectra suggested an extremely energetic explosion of a massive carbon-oxygen star (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999). Since the energy was more than 10 times that of a canonical core-collapse supernova, the term “hypernova” was suggested for this event (Iwamoto et al. 1998). The mass of \(^{56}\text{Ni}\) needed to power the early light curve in these models (0.5 – 0.7 \( M_\odot \)) is much larger than the \( \leq 0.1 \ M_\odot \) typical for “normal” core-collapse supernovae (Patat et al. 1994; Schmidt et al. 1994). This large mass of \(^{56}\text{Ni}\) for SN 1998bw was disputed by Höflich, Wheeler, & Wang (1999), who found that the early light curve can also be reproduced by an asymmetric Type Ic supernova (SN) ejecting only 0.2 \( M_\odot \) of \(^{56}\text{Ni}\), given the right viewing angle and degree of asymmetry.

The models for SN 1998bw differ considerably in terms of progenitor mass, nickel mass, and explosion energy. We therefore focus on the late-time evolution, when the nucleosynthesis and density distribution can be studied directly. The total emission in the nebular phase is also less sensitive to asymmetries compared to the early light curve.

We present photometry and spectroscopy of SN 1998bw up to 500 days past explosion. We also compare these with results from spectral synthesis based on various progenitor models. A more detailed analysis will be given elsewhere.

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2. OBSERVATIONS, REDUCTIONS, AND RESULTS

2.1. Photometry
Photometry was obtained at eight epochs between 33 and 504 days past explosion using the ESO 3.6 m telescope on La Silla and the VLT/UT1 on Paranal. The images were bias-subtracted and flat-fielded using IRAF.

To obtain the supernova magnitudes, we used DAOPHOT. The instrumental magnitudes were converted using local standards from T. J. Galama et al. At the earliest epochs, the errors are estimated as the standard deviations in the magnitudes of the local standards. They also encapsulate the neglect of color transformations.

At later phases, the main uncertainty lies in the background subtraction, since the supernova is superposed on an H\(\alpha\) region. We constructed template point-spread functions (PSFs) using one or several stars, and the best PSF was chosen from judgments of the subtracted images. This PSF was subtracted from the SN position with a range of magnitudes, and the SN magnitude was taken as the one that gave the smoothest background after subtraction. Upper and lower limits were estimated by noting when the subtracted image showed a hole, or a clear point source, at the supernova position. The supernova magnitudes are given in Table 1 and plotted in Figure 1.

2.2. Spectroscopy
Spectroscopic observations were also obtained to late phases (Fig. 2). At ESO 3.6 m we used EFOSC2 with grisms 11 and 12, and at VLT/UT1 we used FORS1 with the 300 grisms. All spectra were bias-subtracted, flat-fielded, and wavelength-calibrated. Flux calibration was done with a spectrophotometric standard star, and the absolute fluxing was performed using the simultaneous V-band photometry. All spectra were taken close to the parallactic angle to reduce differential refraction.

The spectral evolution of SN 1998bw from day 33 to day 504 is shown in Figure 2. The evolution of the spectra in the nebular phase is fairly slow. The [O\(\text{I}\)] \(\lambda\lambda6300, 6364\) are the strongest lines, and the 7300 and 8600 \(\AA\) features, likely to be due to Ca \(\text{II}\), decrease in strength relative to the [O\(\text{I}\)] lines. Other prominent features are seen at \(\sim 4570\) and 5890 \(\AA\) and are probably due to Mg \(\text{I}\) (or [Fe \(\text{III}\)]) and Na \(\text{I}\) D (and possibly He \(\text{I}\)), respectively.
3. DISCUSSION

3.1. General Considerations

A lower limit of 0.22 $M_\odot$ of $^{56}$Ni for SN 1998bw was achieved by McKenzie & Schaefer (1999) by comparing the $V$ magnitude at 170 days to that of SN 1987A. While the light curve of SN 1987A closely followed the decay rate of $^{56}$Co, suggesting full trapping of the gamma rays, the light curve of SN 1998bw fell substantially faster. The assumption of full trapping at 170 days in SN 1998bw used by McKenzie & Schaefer is clearly too conservative. In fact, the light curve of SN 1998bw is similar to that of many other Type Ib/c SNe (Clocchiatti & Wheeler 1997; Sollerman, Leibundgut, & Spyromilio 1998) and can be reproduced by a simple model of a radioactively powered ejecta leaking gamma rays due to homologous expansion (Fig. 1). If the decay would follow full trapping from day 64 and onward, the flux in the $V$ band at day 170 would be 2.4 times brighter than actually observed (Fig. 1). Assuming full trapping at day 64 (at the beginning of the fast decay) then provides an upper limit of $\sim$41% on the trapping at day 170, increasing the lower limit of the Ni mass to $\sim$0.5 $M_\odot$.

The above estimate depends, however, on the bolometric correction and its evolution for these supernovae. That the bolometric decay rate is similar to that of the $V$ band at this epoch is indicated by the simple estimates of the bolometric luminosity by McKenzie & Schaefer (1999). This is also confirmed by our detailed modeling (see below) and supported by the fit to the $V$ curve by the simple gamma-leakage model. However, the bolometric correction could still be different for SN 1987A and SN 1998bw. If SN 1998bw emitted a smaller fraction of its bolometric luminosity in the optical range than SN 1987A, its Ni mass would be overestimated.

Adopting a distance of 35 Mpc ($H_0 = 72$), a reddening of $E(B-V) = 0.06$ (Schlegel, Finkbeiner, & Davis 1998), and integrating our spectrum at day 141 gives a luminosity ($L_{\text{opt}} = 3.5 \times 10^{41}$ ergs s$^{-1}$) that requires 0.1 $M_\odot$ of $^{56}$Ni. This limit on the Ni mass clearly has to be corrected upward because of the two assumptions made: the assumption of full gamma-ray trapping and the assumption that the spectrum contains the full bolometric luminosity. With the same argument as above, no more than 48% of the energy is deposited at 141 days. Furthermore, detailed models (see below) show that the observed spectrum contains only 71% of the total flux. These corrections indicate that the lower limit must be increased to 0.3 $M_\odot$. The dominant errors are the uncertainties in bolometric correction ($\sim$10%), distance, and reddening for SN 1998bw. Allowing for a 15% uncertainty in the distance scale and $\pm 0.1$ mag in $V$, makes the absolute fluxes (and the Ni mass) uncertain by $\sim$35%.

3.2. Detailed Modeling

To obtain more quantitative estimates of the Ni mass, detailed modeling is required. Our analysis uses an updated version of the spectral code in Kozma & Fransson (1998a, 1998b). At the epochs discussed here, the ejecta emission is powered by the radioactive decay of $^{44}$Co. The deposition of the resulting gamma rays and positrons is modeled in detail according to Kozma & Fransson (1992). The ionization and heating is balanced by thermal and radiative processes, producing the observed optical and infrared emission. This time-dependent code gives good agree-
ment with light curves and late-time spectra for SN 1987A (Kozma & Fransson 1998a, 1998b; Kozma 2000).

As input models we use different combinations of unmixed and artificially mixed models of SN 1998bw, based on the CO138 model calculated by Iwamoto et al. (1998) and the CO6 model from Woosley et al. (1999). Both models are spherically symmetric explosions of massive carbon-oxygen stars. The CO138 model has a mass $M_{\text{CO}} = 13.8 M_\odot$, explosion energy $E_{\text{exp}} = 3 \times 10^{52}$ ergs, and mass of $^{56}\text{Ni}$ $M(^{56}\text{Ni}) = 0.7 M_\odot$. Such a carbon-oxygen core corresponds to a zero-age main-sequence (ZAMS) star of $M_{\text{ZAMS}} \sim 40 M_\odot$. The CO6c model with $M_{\text{CO}} = 6.55 M_\odot$, $E_{\text{exp}} = 2.2 \times 10^{52}$ ergs, and $M(^{56}\text{Ni}) = 0.47 M_\odot$ corresponds to a $M_{\text{ZAMS}} \sim 25 M_\odot$ star.

In Figure 3 we show our modeled spectra together with the observations at 141 days. From the observed line profiles, we conclude that mixing is important. Calculations based on non-mixed models give very broad and flat-topped line profiles, which are not seen in the observations. In the mixed models, we have also decreased the expansion velocities to get better agreement with the observed line widths. A mixed model with the original velocities results in nicely peaked, but too broad, line profiles. A decrease in velocity results in an increase of the densities given by the original explosion models. We have increased the densities by factors of 10–100, except in the Fe-rich regions in which it is kept unchanged (see below). These changes also affect the kinetic energy in the modified models. In the layers below $\sim 12,000$ km s$^{-1}$, which is the only material that contributes significantly to the emission at late times, the kinetic energies are $2 \times 10^{51}$ ergs (CO6) and $5 \times 10^{51}$ ergs (CO138), respectively. Note that our analysis is not sensitive to the high-velocity gas, which might also contain a significant amount of energy. Early-time analysis is therefore more reliable for determining the total kinetic energy of the explosion. As seen in Figure 3, the synthetic line profiles are still somewhat broader than those observed. We can overcome this by decreasing the velocities even more, but the high density in the oxygen-rich regions then results in strong O i lines at 5577, 7774, and 9265 Å, which are not seen in the observations.

Most features in the observed spectrum have a counterpart in the modeled spectra, and in Figure 3 we include some of the line identifications. The 4000–5500 Å regime is problematic, and preliminary results from improved models suggest that most of these features are a mixture of Fe ii and Fe iii lines. The models presented here have too low a degree of ionization, with mostly Fe i and Fe ii emission. A higher density in the Fe-emitting material would result in even lower ionization, which is why we do not increase the density in the Fe-rich regions. The ionization can instead be increased by decreasing the density in these regions. Scattering and fluorescence may also play a significant role in understanding these features. We therefore regard the Fe i emission as dubious.

3.3. The Light Curve

In Figure 1 we show the light curves from our calculations of the mixed CO6 and CO138 models (solid lines) and from the original, unmixed models (dotted lines). The CO138 model is brighter than CO6. This is not only due to the higher Ni mass, but also a result of the higher ejecta mass ($M_{\text{e}}$) and lower expansion velocity ($v_{\text{max}}$), giving a larger optical depth to the gamma rays ($\tau$); $\tau \propto M_{\text{e}} v_{\text{max}}^{-1}$.

The effect of changing the expansion velocities can also be seen in Figure 1. While the two CO6 models have the same Ni mass and ejecta mass, they differ in expansion velocity. The mixed models are somewhat brighter than the unmixed models, due to the higher gamma-ray optical depth for the models with lower velocities. In the original CO6 model, we find that at 200 (400, 600) days only $\sim 7.2\%$ (4.4%, 3.9%) of the energy released in the $^{56}\text{Co}$ decays is deposited in the ejecta. Out of this energy, $\sim 47\%$ (78%, 87%) is from the kinetic energy of the positrons. For the mixed CO6 model with decreased velocities, $\sim 11\%$ (5.7%, 4.5%) of the energy is deposited.

From the light curves, and within the framework of our modeling, we conclude that the nickel mass needed to power the late emission is indeed very high. For the two models that best reproduce the late-time observations, we calculate the deposition of the radioactive energy and thus the required mass of nickel. The CO6 model requires 0.9 $M_\odot$ of $^{56}\text{Ni}$ to maintain the luminosity at 340–410 days. The CO138 model, which traps 10% of the energy at 400 days, requires 0.5 $M_\odot$. The errors on these estimates are dominated by the uncertainty in distance and reddening stated in § 3.1.

Höflich et al. (1999) found that the early light curve of SN 1998bw could be explained in terms of a more “normal” Type Ic SN, which ejected 0.2 $M_\odot$ of $^{56}\text{Ni}$, given the right degree of asymmetry. However, at the nebular phase studied here the ejecta are optically thin, and for a given density structure the luminosity is not as sensitive to asymmetries as is the early light curve. By modeling the late-time line profiles, providing a measure of the energy input with velocity, we get a handle on the distribution of the ejecta and can therefore model the gamma-deposition self-consistently.

The Ni mass determined for the CO138 model is close to the lower limit from § 3.1. This is because this massive model closely represents the maximum trapping allowed by the observed light curve. Also, since the mixed CO6 model is already dominated by positrons at 400 days, the estimated Ni mass for this model must be close to the upper limit.

While SN 1998bw ejected a large mass of $^{56}\text{Ni}$, a few other supernovae have shown very low amounts of ejected $^{56}\text{Ni}$ (SN 1994W [$\leq 0.015 M_\odot$; Sollerman, Cumming, & Lundqvist 1998] and SN 1997D [$\leq 0.002 M_\odot$; Turatto et al. 1998]). The iron yield from core-collapse supernovae thus seems to vary substantially.

At very late phases (>400 days), the low energy input means...
low temperatures for the ejecta, and most of the emission in our models comes out in the infrared. The optical light curves no longer directly follow the bolometric light curve. After 400 days, the model light curves drop faster than the observations. A reduced density in the Fe-rich material (§ 3.2) can increase the temperature and boost in particular the \( V \) curve at late phases.

Another possible source for the powering at late phases is interaction with a circumstellar medium (CSM). The absence of H and He in the spectra means that substantial amounts of such gas should be present. Models of the radio emission indicate that some interaction is already taking place (Li & Chevalier 1999), although the CSM density in these models is probably too low to affect the optical light curve, as the wind velocity is high (\( \sim 2000 \text{ km s}^{-1} \)). We see no significant spectroscopic signature that indicates CSM interaction in our late spectra.

4. SUMMARY

We present photometry and spectroscopy of SN 1998bw up to 500 days past explosion. Starting with two different spherically symmetric explosion models, we calculate late-time spectra and light curves using a detailed spectral synthesis code to model our observations. We conclude that mixing is important, and we also have to alter the density distribution macroscopically to obtain reasonable agreement with the line profiles in the observed spectra.

Representing the supernova density profile with the distribution that best reproduces the late-time observations, we calculate the deposition of the radioactive energy and determine how much \(^{56}\text{Ni}\) is required to produce the late-time luminosity. We find that a large amount, roughly \( 0.5 \, M_\odot \), is needed to power the light curve 1 yr after the explosion, although the exact number depends on the chosen explosion model.

Evidence for asymmetries in SN 1998bw comes from early polarization measurements (Kay et al. 1998). The modeling presented here is restricted to the available symmetric models, although the importance of mixing may point to an asymmetric explosion. Whether asymmetric models can reproduce the observations is of interest for future studies.

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REFERENCES

Clocchiatti, A., & Wheeler, J. C. 1997, ApJ, 491, 375
Galama, T. J., et al. 1998, Nature, 395, 670
Höflich, P., Wheeler, J. C., & Wang, L. 1999, ApJ, 521, 179
Iwamoto, K., et al. 1998, Nature, 395, 672
Kay, L. E., Halpern, J. P., Leighly, K. M., Heathcote, S., Magalhaes, A. M., & Filippenko, A. V. 1998, IAU Circ. 6969
Kozma, C. 2000, Mem. Soc. Astron. Italiana, in press (astro-ph/9903405)
Kozma, C., & Fransson, C. 1992, ApJ, 390, 602
———. 1998a, ApJ, 496, 946
———. 1998b, ApJ, 497, 431
Kulkarni, S. R., et al. 1998, Nature, 395, 663
Li, Z.-Y., & Chevalier, R. A. 1999, ApJ, 526, 716
McKenzie, E. H., & Schaefer, B. E. 1999, PASP, 111, 964
Patat, F., et al. 1994, A&A, 282, 731
———. 2000, ApJ, submitted
Patat, F., & Piemonte, A. 1998, IAU Circ. 6918
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schmidt, B. P., et al. 1994, AJ, 107, 1444
Sollerman, J., Cumming, R. J., & Lundqvist, P. 1998, ApJ, 493, 933
Sollerman, J., Leibundgut, B., & Spyromilio, J. 1998, A&A, 337, 207
Turatto, M., et al. 1998, ApJ, 498, L129
Woosley, S. E., Eastman, R. G., & Schmidt, B. P. 1999, ApJ, 516, 788