SN 1998bw/GRB 980425:

Hypernova or Aspherical Explosion?

Peter Höflich, J. Craig Wheeler, Lifan Wang

Department of Astronomy, University of Texas, Austin, TX 78712, USA
E-Mail: pah@alla.as.utexas.edu, lifan@tao.as.utexas.edu, wheel@alla.as.utexas.edu

ABSTRACT

The recent discovery of the unusual supernova SN1998bw and its apparent correlation with the gamma-ray burst GRB 980425 has raised new issues concerning both the GRB and SNe. SN1998bw was unusually bright at maximum light and expansion velocities were large making SN1998bw a possible candidate for a “hypernova” with explosion energies exceeding $10^{52}$ erg. We show that the light curve of SN1998bw can be understood as the result of an aspherical explosion along the rotational axis of a basically spherical, non-degenerate C/O core of a massive star with an explosion energy of $2 \times 10^{51}$ erg, a total ejecta mass of $2M_\odot$, and a $^{56}Ni$ mass of $0.2M_\odot$ if it is seen from high inclinations with respect to the plane of symmetry. In this model, the high expansion velocities are a direct consequence of the aspherical explosion which, in turn, produces oblate isodensity contours. This suggests that the fundamental core-collapse explosion process itself is strongly asymmetric.

Subject headings: Supernovae: general, individual (SN 1998bw) — gamma-ray bursters — radiation transfer — asphericity
1. Introduction

Due to its correlation in time and location, the γ-ray burst GRB 980425 has a high probability of being associated with SN 1998bw (Galama et al. 1998). This connection is supported by the association of a relativistically expanding radio source with SN 1998bw (Kulkarni et al. 1998). From optical spectra, SN 1998bw was classified as a SN Ic by Patat and Piemonte (1998). What sets SN 1998bw apart from other SNe Ic are higher expansion velocities as indicated by the Si II and Ca H and K lines (≈30 to 50 percent higher at maximum light than SN1994I and SN1983V, Clochiatti & Wheeler 1997), the red colors at maximum light, and the large intrinsic brightness. A peak luminosity of $1.3 \pm 0.6 \times 10^{43} \text{erg/s}$ can be inferred from the redshift of the host galaxy ($z = 0.0085$, Tinney et al. 1998) and the reddening ($A_V = 0.2^m$, Schlegel et al. 1998), if we assume $H_o = 67 \text{ km/s/Mpc}$. The uncertainties are rather large as the host galaxy is not yet fully in the Hubble flow, so the peculiar velocity may be of the order of 300 to 400 km/sec. $H_o$ is known only to an accuracy of $\approx 10\%$, and $A_V$ may vary by $\approx 0.1^m$.

The properties of SN 1998bw suggest that it was a “hypernova” event (Paczyński 1997). Based on their light curve (LC) calculations, Iwamoto et al. (1998) and Woosley et al. (1998) derived explosion energies of 20-50 foe and 22foe ($1 \text{ foe} = 10^{51} \text{ erg}$) ejecta masses of 12-15 $M_\odot$ and 6 $M_\odot$, and $^{56}\text{Ni}$ masses of 0.6-0.8 and 0.5 $M_\odot$, respectively. These models have some problems. Although Iwamoto’s fit of the LC is excellent with errors $\lesssim 0.3^m$ over 40 days, the spectra show absorption lines that are too narrow by a factor of 2 to 3 indicating too narrow a range of formation in velocity space. This may be related to the high envelope mass. In the lower mass models of Woosley et al. (1998), the bolometric and monochromatic LCs differ from the observations by 0.5 to 1 magnitude over the course of 20 days and all the computed color indices (B-V, V-R, V-I) are too red by about the same amount at all epochs.

Guided by the deduced properties of more traditional core collapse SNe and SNe Ic in particular, we want to demonstrate that asphericity is an alternative explanation for SN 1998bw that puts it back into the range of “normal” SNe Ic.

Both spectral analyses and LC calculations support the picture that SNe II, SNe Ib and SNe Ic may form a sequence involving core collapse with successively smaller H and He envelopes (Clochatti & Wheeler 1997). The analysis of spectra and LCs gives essentially no insight into the geometry of the expanding envelope. Polarization, however, provides a unique tool to explore asymmetries. Linear polarization of $\approx 1\%$ seems to be typical for SNe II (Wang, Wheeler & Höflich 1998). There is a trend, however, for the observed polarization to increase in core-collapse SNe with decreasing envelope mass, e.g. from SN II to SN Ic (Wang et al. 1998). For SN 1993J, the observed linear polarization was as high as $\approx 1.0\ldots1.5\%$, and for the SN Ic 1997X the polarization was even higher (Wang et al. 1998). This trend, while tentative, clearly points toward the interpretation that the explosion itself is strongly asymmetric.

From theoretical calculations for scattering dominated atmospheres, this size of polarization, $\gtrsim 1\%$, requires axis ratios of the order of 2 to 3, making these objects highly aspherical. The luminosity $L(\Theta)$ will change by a factor of $\approx 2$ as the line of sight varies from the equator to the pole (Höflich 1991, Höflich et al. 1995).

Given the ubiquitous presence of polarization in core collapse supernovae and especially SN Ic, inclusion of asphericity effects in SN Ib/c may prove to be critical (Wang et al. 1998). Polarization has been observed in SN1998bw (Kay et al. 1998).

In this work, we present a first approach to the problem of asymmetric LCs for SN Ic and SN 1998bw.

2. Description of the Concept and Numerical Methods

For the initial setup, we use the chemical and density structures of spherical C/O cores of Nomoto and Hashimoto (1988). These structures are scaled to adjust the total mass of the ejecta. This is an approximation, but the details of the chemical profiles are not expected to effect the light curves.

The explosion models are calculated using a one-dimensional radiation-hydro code which includes a detailed nuclear network. The code also simultaneously solves for the radiation transport via moment equations. Photon redistribution and thermalization is based on detailed NLTE-models. Several hundred frequency groups are used to calculate monochromatic LCs, frequency-averaged Eddington factors and opacity means. A Monte Carlo scheme is used for γ-rays. For details, see Höflich, Wheeler & Thielemann (1998) and references therein.
Aspherical density structures are constructed based on the spherical density distribution. For the simple models presented here, we impose the asymmetry after the ejecta has reached the homologous expansion phase. We generate an asymmetric configuration by preserving the mass fraction per steradian from the spherical model, but imposing a different law of homologous expansion as a function of the angle Θ from the equatorial plane. For typical density structures, a higher energy deposition along the polar axis results in oblate density structures. Such an energy pattern may be produced if jet-like structures are formed during the central core collapse as suggested by Wang & Wheeler (1998). In contrast, a prolate density structure would be produced if more energy is released in the equatorial region than in the polar direction. For more details, see Höflich, Wang & Wheeler (1998).

The bolometric and broad band LCs are constructed by convolving the spherical LCs with the photon redistribution functions \( L(\Theta)/L(\text{mean}) \) which are calculated by our Monte Carlo code for polarization (Höflich 1991, Höflich et al. 1995). Typical conditions at the photosphere and therefore the colors are expected to be similar in both the spherical and aspherical models because the energy flux \( F(\Theta) \) is found to be similar both in the spherical and aspherical configuration to within \( \approx 40\% \). To first order (Wien’s limit), a change of \( F(\Theta) \) by 40% corresponds to a change in color indices by about 0.1 m. Stationarity is assumed to calculate the photon redistribution functions since the geometry does not change during the typical diffusion time scale. We assume implicitly the same mean diffusion time scales for both the spherical and aspherical configurations. This mostly effects the very early phases of the LC when the hydrodynamical time scales are short. For more details, see Höflich, Wang & Wheeler (1998).

### 3. Results

We construct models in such a way that at day 20 the axis ratio at the photosphere is 2. In comparison to the spherical model, the homology expansion parameters are a factor of \( \approx 2.2 \) larger along the pole for oblate ellipsoids and a factor of \( \approx 1.5 \) larger for prolate ellipsoids along the equator.

We first calculated aspherical LCs based on the C/O core CO21 which gives a good representation of the BVRI LCs of the SN Ic 1994I (Iwamoto et al. 1996). The ejecta mass is \( 0.8M_\odot \) and the explosion energy is \( E_{\text{kin}} = 10^{51} \text{erg} \). A mass of 0.08 \( M_\odot \) of \( ^{56}\text{Ni} \) is ejected. This model failed to produce the peak brightness by a factor of 2, gave too short a rise time by about 5 days, and shows blue color indices at maximum light.

To boost the total luminosity to the level of observation we increased the amount of ejected \( ^{56}\text{Ni} \) to \( 0.2M_\odot \). This quantity of nickel is still below the estimates for \( ^{56}\text{Ni} \) of 0.3 \( M_\odot \) in the bright SN II 1992am (Schmidt et al. 1997). As shown in Fig.1, the time of maximum light is rather insensitive to asphericity effects. The need to delay the time to maximum and to produce the red color at maximum light suggested the need to increase the ejecta mass with an appropriate increase in the kinetic energy to provide the observed expansion. We thus computed a series of models with \( M_{ej} = 2M_\odot \) \( E_{\text{kin}} = 2 \times 10^{51} \text{erg} \) and \( M_{Ni} = 0.2M_\odot \).

Asphericity of the amplitude assumed here can change the luminosity over a range of roughly 2 magnitudes (Fig. 1). For oblate ellipsoids, the luminosity is enhanced along the pole whereas for prolate structures the enhancement occurs in the equatorial direction. Combined with the polarization properties, this provides a clear separation between oblate and prolate geometries as \( P \) always goes to 0 if the structure is seen pole-on and \( P \) increases towards lower latitudes (Höflich 1991).
Observations of the polarization of SN 1998bw 23 days after the explosion show little polarization (< 1%, Patat et al. 1998). By day 58, the intrinsic polarization was reported to be 0.5 percent (Kay et al. 1998). Polarization data on SN Ic is rare, but this value is less than seen in some SNe Ic and related events (see above). SN 1998bw was also rather bright. This combination implies oblate geometries if asymmetry is involved.

For the comparison between the observed and theoretical LCs (Fig. 2), we have used the relative calibration of Woosley et al. (1998) for the "bolometric LC". The broad-band data was obtained from Galama et al. (1998). Apparently, the object must be seen from an angle of ≥ 60° from the equator. The same conclusion can be drawn independently from the detected but relatively small linear polarization.

Overall, the broad-band LCs agree with the data within the uncertainties. The intrinsic color excess B-V matches the observations within 0.1 m and, after the initial rise of ≈ 7 days, the agreement in each band is better than 0.3 m. The main discrepancy with the observations occurs during the initial rise when the diffusion time scales are much longer than the expansion time. Under these conditions, our approximation of redistribution of the energy of a spherical model breaks down since the diffusion time scale is long compared to the hydrodynamical time scale. The decline after maximum is slightly too steep in the models both in the bolometric and broad band LCs. This is likely to be related to the energy generation in the envelope by γ-ray deposition or to the change in the escape probability of low energy photons. The decline rate immediately after peak can be reduced by increasing the amount of radioactive 56Ni by ≈ 40%. An alternative means to flatten the light curve is to reduce the increase in escape probability. This can be achieved by a modification restricted to the inner layers of the ejecta because the escape probability is determined by those layers. Either the expansion velocity of the inner layers can be reduced or the density gradient may become steeper. Both are expected for strongly aspherical explosions.

4. Discussion and Conclusions

We have shown that the high apparent luminosity of SN 1998bw may be understood within the frame-work of “classical” SN Ic. Even with our current model, SN 1998bw remains at the bright end of the scale. We note that the luminosity of SN 1998bw may be uncertain by a factor of 2 due to non-Hubble motion within the cluster and uncertainties in the Hubble constant and reddening. For a model with an ejected mass of 2 M⊙, an explosion energy of 2 × 1051 erg, and a 56Ni ejection of 0.2 M⊙, both the bolometric and broad-band LCs are rather well reproduced by an oblate ellipsoid with an axis ratio of 0.5 which is observed within 30 deg of the symmetry axis. This angle for the line of sight is consistent with the low (but still significant) polarization observed for SN 1998bw. In a Lagrangian frame, the polar expansion velocity is a factor of 2 larger than the mean velocity. This is also in agreement with the rather large expansion velocities seen in SN 1998bw.

Woosley et al. (1998) have analyzed the possibility of γ-ray bursts in the framework of spherical models. Even with their explosion energies of more than 20 foe they showed that the γ-ray burst associated with SN 1998bw/GRB 980425 cannot be explained by the acceleration of matter to relativistic speeds at shock-breakout. In our picture, the specific energy released in the polar region is comparable. We want to stress, however, that our asymmetry in the energy distribution is set after homologeous expansion is established. Because the early hydrodynamical evolution will rather tend to wipe out asymmetries, the initial anisotropy in the energy distribution is expected to be
significantly higher. How much, only detailed multi-dimensional hydro-calculations can tell.

We have shown that SN 1998bw may be understood within the framework of “classical” core collapse supernovae rather than by a , “hypernova”, but the actual model parameters must be regarded as uncertain both because of the model assumptions and the uncertainty in the observed luminosity. In light of the good fits of Iwamoto et al. (1998), however, SN 1998bw may indeed be a , ”hypernova”. Continuous measurements of the polarization and the velocity of $^{56}$Co lines are critical to unravel the nature and geometry of this object. For more details, see Höflich, Wheeler & Wang (1998).

ACKNOWLEDGMENTS

We thank Ken Nomoto for providing us with the monochromatic LC data in digital form. This research was supported in part by NSF Grant AST 9528110, NASA Grant NAG 5-2888, and a grant from the Texas Advanced Research Program.

REFERENCES

Cliochiatti A., Wheeler J.C. 1997, in: Thermonuclear Supernovae, eds. Ruiz-Lapuente, R. Canal & J. Is-ern, (Dordrecht:Kluwer), Series C, Vol. 486, p. 863

Galama T.J. et al. , 1998, Nature, submitted and astro-ph/9806172

Höflich P., 1995, ApJ, 443, 89

Höflich P. 1991, A&A, 246, 481

Höflich P., Wheeler J.C., Hines D., Trammell S. 1995, ApJ 459, 307

Höflich P., Wheeler J.C., Thieleman F.K. 1998, ApJ 495, 617

Höflich P., Wheeler J.C., Wang L. 1998, ApJ, submitted

Iwamoto K., Nomoto K., Höflich P., Yamaoka H., Ku-magai S., Shigeyama T. ApJ 437, L115 and astro-ph/9806382

Iwamoto K. et al., 1998 Nature, submitted

Kay L.E., Halpern J.P., Leighly K.M., Heathcote S., Magalhaes A.M. 1998, IAU-Circular 6969

Kulkarni S.R. Nature, submitted, and astro-ph/9806364

Nomoto K., Hashimoto M. 1988, Phys. Rep. 163, 13

Patat G., Piemonte A. 1998, IAU-Circ. 6918

Paczyński B. 1997, ApJ 494, L45

Schlegel D.J., Finkbeiner D.P., Davis M. 1998, ApJ, in press

Schmidt B. et al. 1997, AJ 107, 1444

Tinney C., Stathakis R., Cannon R., Galama T.J. 1998, IAU Circ. 6896

Wang L., Wheeler J.C., Höflich P., Wang L. 1998, in: ”SN1987A: Ten Years Later”, eds. M.M. Phillips & N.B. Suntzeff, (Dordrecht:Kluwer), in press

Wang L, Wheeler J.C. 1998, ApJ Let., in press

Woosley S., Eastman R., Schmidt B. 1998, ApJ, submitted