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Supernovae in Three-Dimension: A Link to Gamma-Ray Bursts

Keiichi Maeda ⋆

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85741 Garching, Germany

Abstract Observational consequences of a jet-driven supernova (SN) explosion model are presented. The results are compared in detail with optical observations of SN 1998bw associated with a Gamma-Ray Burst. It is shown that the jet model is able to reproduce virtually all the optical observations available for this SN, although a spherical model fails to explain some of observed features. Because of the viewing angle effect, the required kinetic energy of the SN ejecta is reduced to $\sim 2 \times 10^{52}$ erg as compared to that obtained by the previous spherical model ($\sim 5 \times 10^{52}$ erg), but this is still much larger than that of a canonical SN ($\sim 10^{51}$ erg).

Key words: supernovae: individual (SN 1998bw) — gamma rays: bursts — radiative transfer — nuclear reactions, nucleosynthesis, abundances

1 INTRODUCTION

Supernovae (SNe) are discovered to date in association with three Gamma-Ray Bursts (GRBs), i.e., GRB980425 (SN Ic 1998bw), GRB 030329 (SN Ic 2003dh), and GRB031203 (SN Ic 2003lw) (see e.g., Woosley & Bloom 2006 for a review). An SN Ic (see e.g., Filippenko 1997 for a review of SN terminology) is a class of SNe resulting from a core-collapse of a C+O star, which has lost its hydrogen envelope (and probably even a large fraction of the helium envelope) before the explosion (e.g., Nomoto et al. 1995).

The three SNe Ic associated with GRBs share similar properties in the early phase. The spectra show very broad absorption features, and the light curve width is also broad as compared to canonical SNe Ic (e.g., Mazzali et al. 2006). These properties are explained by a combination of large kinetic energy ($E_{\rm K}$) and large mass of the SN ejecta ($M_{\rm ej}$), i.e., $E_{51} \equiv E_{\rm K}/10^{51}$ erg $\sim (3-5)$ and $M_{\rm ej} \sim 10\,M_{\odot}$ (Iwamoto et al. 1998; Mazzali et al. 2003; Mazzali et al. 2006). The energy is more than 10 times larger than in canonical SNe, thus these energetic SNe are sometimes called "hypernovae". $M_{\rm ej} \sim 10\,M_{\odot}$ (i.e., the mass of the C+O star $M_{\rm CO} \sim 12-14\,M_{\odot}$) corresponds to the main-sequence mass $M_{\rm ms} \sim 30-40\,M_{\odot}$. The peak luminosity indicates that $M(^{56}{\rm Ni}) \sim 0.3-0.6\,M_{\odot}$, larger than in canonical SNe.

In this paper, we show observational consequences of a jet-driven SN explosion model as suggested by Maeda et al. (2002) (see also Maeda & Nomoto 2003b) for SN 1998bw. First we summarize the hydrodynamic model of the jet-driven explosion (Sect. 2). Then, after summarizing numerical methods to compute radiation processes in a multi-dimensional SN model, expected observational consequences are shown in Section 3 with detailed comparisons with observations of SN 1998bw. The paper is closed with conclusions in Section 4.

2 HYDRODYNAMIC MODEL

The massive progenitor for SNe associated with GRBs ($M_{\rm ms} \sim 40\,M_{\odot}$) suggests that the central remnant is a black hole (BH) rather than a neutron star (NS). The large kinetic energy suggests that the explosion mechanism is totally different from a canonical SN. Most favorable scenario is a formation of a BH and a hyper-accreting disk, e.g., the collapser model (Woosley 1993; MacFadyen & Woosley 1999).

⋆ E-mail: maeda@MPA-Garching.MPG.DE

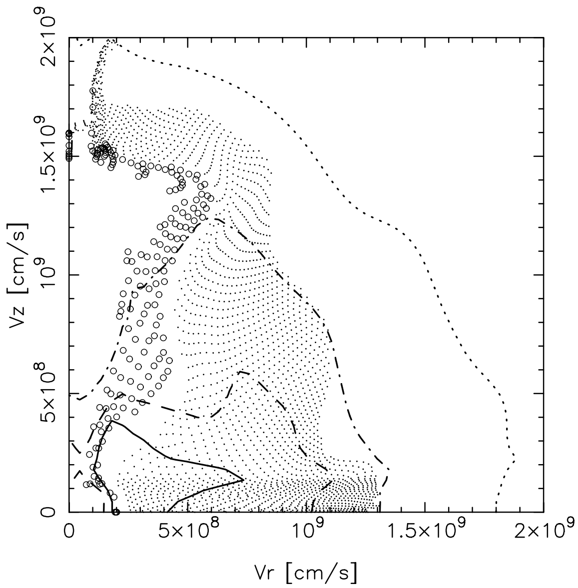

Fig. 1 Structure of the jet-like SN ejecta at a homologous expansion phase (valid after ~ 1 day and thereafter). Distribution of ^{56}Ni (open circles) and of ^{16}O (dots) are shown. The contours are for density distribution. See Maeda et al. (2002) for details.

The system of this kind is expected to produce an aspherical explosion, irrespective of detailed physical processes to create a highly relativistic jet (responsible to a GRB) and a sub-relativistic bulk flow (responsible to a hypernova). Nucleosynthesis in the stellar mantle as a consequence of the jet-driven explosion was studied by several authors (Nagataki 2000; Maeda et al. 2002; Maeda & Nomoto 2003b; Nagataki et al. 2003). The general feature is that the explosive nucleosynthesis takes place more actively in the jet direction (z) than in the equatorial direction (r), resulting from the stronger shock and the higher temperature in the jet direction (Fig. 1). In the z-direction, ^{56}Ni is synthesized abundantly, while in the r-direction unburned oxygen is left.

3 RADIATION TRANSFER IN THREE-DIMENSION

To test a multi-dimensional explosion model, one has to solve radiation transport in multi-dimensional space. We have developed the *SAMURAI* code – the *SupernovA MUlti-dimensional RAdIative transfer* code. We adopt the Monte-Carlo method to follow photon packets. Transport of γ-rays (Maeda 2006b) and optical photons (Maeda et al. 2006c) is solved to synthesize a bolometric optical light curve and multi-energy light curves in the keV – MeV range. Then spectrum calculations are performed for optical photons at the early phase (Tanaka et al. 2006) and at the late phase (Maeda et al. 2006a). See also Höflich et al. (1999), Thomas et al. (2002), Kasen et al. (2004), Kozma et al. (2005), and Sim (2006) for other multi-dimensional codes available to date.

Figure 2 shows the optical light curve of SN 1998bw associated with GRB980425 (Maeda et al. 2006c). The spherical model with $E_{51} = 50$ fits the early phase light curve fairly well. The aspherical model with $E_{51} = 20$ yields a fit as nice as, or even better than, the spherical model with $E_{51} = 50$. In the early phase, the ejecta are optically thick. Thus, the diffusion time scale is determined by the optical depth along the line-of-sight. Since $E_{\rm K}/M_{\rm ej}^3$ (see Discussion) is effectively large for the jet model if viewed on-axis, the diffusion time scale is effectively small in this direction. Thus the smaller energy is required than the spherical model.

The LC computation by the *SAMURAI* code thus shows that the early phase observation can be reproduced either by the spherical model or by the aspherical model (see also Höflich et al. 1999). This is found to also be the case for the early phase spectra (Tanaka et al. 2007). The degeneracy can be resolved by modeling the late-phase observations. Figure 2 shows that the spherical model with $E_{51} = 50$ is too faint as compared to the observation, since $M_{\rm ej}^2/E_{\rm K}$, which gives the efficiency of converting γ-rays to optical photons, is too small (Maeda et al. 2003a). In the late phase, γ-rays can reach at any point of the ejecta not only near ^{56}Ni. The optical photons emitted at every point can reach to the observer. Such that, the luminosity is determined by the global properties in the late phases, rather than the local isotropic properties as in the early phase. In the jet-driven model, $M_{\rm ej}^2/E_{\rm K}$ to fit the early phase observations is larger than the spherical model. This leads to the large luminosity, as large as observed, at the late phase for the jet model (Maeda et al. 2006a). It should be emphasized that the early and late phase observations provide different information

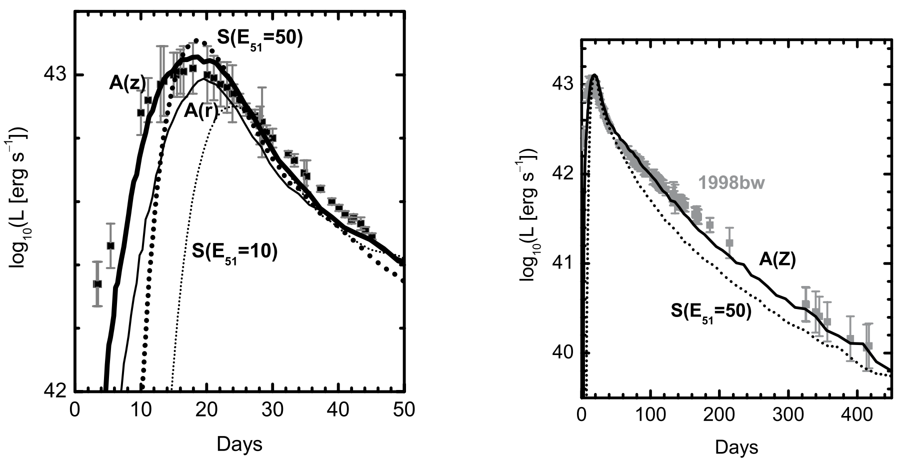

Fig. 2 The light curve of SN 1998bw (gray points) in the early (left) and late (right) phases. Shown here are the jet-driven model with $E_{51} = 20$ as seen at the z- [thick black, denoted as A(z)] and r- [thin solid, A(r)] directions. Also shown are the spherical models (S).

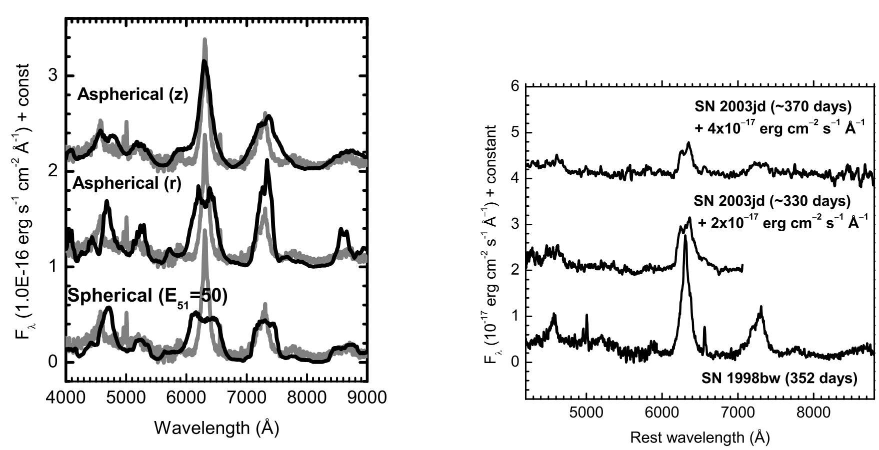

Fig. 3 (Left) Late phase spectrum of SN 1998bw at ~ 1 years after the explosion, as compared with the synthesized spectra of the jet-driven model with $E_{51} = 20$ viewed at z- and r-directions, and the spherical model with $E_{51} = 50$ (black curves, from top to bottom). (Right) Late phase nebular spectra of SN 2003jd taken at the Keck telescope (top) and at the Subaru telescope (middle), as compared with that of SN 1998bw (bottom).

on the SN ejecta – the isotropic values for the former and the intrinsic global values for the latter. The effect, as found by our study with the *SAMURAI* code, is important if the explosion is not spherical.

Finally, late phase spectra provide powerful diagnostics. Figure 3 (left) shows the late phase nebular spectrum of SN 1998bw (Maeda et al. 2002; Maeda et al. 2006a). The spherical model results in the flat-topped [OI]$\lambda\lambda$6300,6363, which is a result of emitting O distributed in a high velocity shell. The jet model yields narrowly peaked [OI] if viewed from the z-direction, and doubly peaked [OI] if viewed from the r-direction. This is a consequence of the emitting O distributed in a disk like structure (Fig. 1). The jet-driven model viewed from the z-direction yields the best fit, although the other models fail to reproduce the characteristic [OI] profile.

The jet model as viewed from the z-axis can explain all the observations available for SN 1998bw in the optical window. This is not the case for the spherical hypernova model (Maeda et al. 2003a; Maeda et al. 2006a; Maeda et al. 2006c). In the jet-driven model, E_{51} is reduced as compared to the spherical model, but still $E_{51} \sim 20$ is much larger than canonical SNe. The jet-driven model for hypernovae was further strengthened by another example – SN Ic 2003jd. It showed broad absorption lines at the early phase, as typical of hypernovae, although it was not associated with a GRB. SN 2003jd in the late phase showed unique [OI] profile - doubly peaked (Fig. 3, right panel). The line profile is nicely reproduced by the jet model viewed side ways (Mazzali et al. 2005).

4 CONCLUSIONS

In this paper, we have presented the first study of deriving observational consequences of a jet-driven supernova model. For SN 1998bw (associated with GRB 980425), we found that the jet-driven model fits optical observations fairly well – the model can explain most of observational facts from ~ 1 week since the explosion to ~ 1 year, although a spherical model can explain only a part of the observations. It is found that the viewing angle should be close to the axis of the jet, as is consistent with the fact that it took place with a GRB. The required kinetic energy of the SN ejecta is reduced to $\sim 2 \times 10^{52}$ erg as compared to the value suggested by the earlier spherical modeling ($\sim 5 \times 10^{52}$ erg), but it is still much larger than the canonical value ($\sim 10^{51}$ erg). This indicates that the explosion mechanism of the SNe associated with GRBs is totally different from that of a canonical SN.

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DISCUSSION

NINO PANAGIA: How much are you confident with the mass of a progenitor star?

KEIICHI MAEDA: For SNe Ic, it is the ejecta mass that is derived by this kind of study. This is directly related to the mass of a C+O star just before the explosion, with small uncertainty in the unknown central remnant's mass. The derived mass of the C+O star is thus more or less reliable. However, we need a specific evolutionary model to convert the C+O core mass to the main-sequence mass. We assume a standard evolutionary scenario, but GRB progenitors may well follow a non-standard evolution. This is indeed an interesting subject to pursue.

ARNON DAR: You showed a scaling law for the peak date of a SN light curve ($\propto M_{\rm ej}^{1/4} E_{51}^{-1/4}$). Is it sensitive to the amount or distribution of ^{56}Ni?

KEIICHI MAEDA: The scaling law is derived by equating the expansion time scale and the diffusion time scale. It is a function of opacity, density, and the distance between the surface and the position of ^{56}Ni. Increasing the amount of ^{56}Ni of Fe-peak elements increases the opacity, thus delays the peak date. In the case of the GRB-associated SNe, this effect is not large, since the opacity is dominated by abundant O-rich materials. The ^{56}Ni distribution is more important in this case. Indeed, the jet-driven model has the extended ^{56}Ni distribution, and this is one of reasons why we can fit the peak data of SN 1998bw with smaller energy than in spherical models.