THREE-DIMENSIONAL SIMULATION OF GAMMA-RAY EMISSION FROM ASYMMETRIC SUPERNOVAE AND HYPERNOVAE

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ABSTRACT

Hard X- and γ-ray spectra and light curves resulting from radioactive decays are computed for aspherical (jetlike) and energetic supernova models (representing the prototypical hypernova SN 1998bw), using a three-dimensional energy- and time-dependent Monte Carlo scheme. The emission is characterized by (1) early emergence of high-energy emission, (2) large line-to-continuum ratio, and (3) large cutoff energy by photoelectric absorption in hard X-rays. These three properties are not sensitively dependent on the direction to the observer. On the other hand, fluxes and line profiles depend sensitively on the direction to the observer, showing larger luminosity and larger degree of blueshift for an observer closer to the polar (z) direction. Strategies to derive the degree of asphericity and the direction to the observer from (future) observations are suggested on the basis of these features, and an estimate of the detectability of the high-energy emission by INTEGRAL and future observatories is presented. Also presented is an examination of the applicability of a gray effective γ-ray opacity for computing the energy deposition rate in the aspherical SN ejecta. Detailed three-dimensional computations show that an effective γ-ray opacity \( \kappa_\gamma \sim 0.025 - 0.027 \text{ cm}^2 \text{ g}^{-1} \) reproduces the detailed energy-dependent transport for both spherical and aspherical (jetlike) geometry.

Subject headings: gamma rays: theory — radiative transfer — supernovae: general — supernovae: individual (SN 1998bw) — X-rays: stars

1. INTRODUCTION

Gamma rays emitted from radioactive isotopes, which are explosively synthesized at a supernova (SN) explosion (Truran et al. 1967; Bodansky et al. 1968; Woosley et al. 1973), play an important and unique role in the emission from a SN, not only at γ-ray energies but also at the lower energies: from X-rays to even the optical or near-infrared (NIR) band. Up to a few years after the explosion, the decay chain \( ^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe} \) (Clayton et al. 1969) dominates the high-energy radiation input to a SN, with minor contributions from other radioactivities such as \( ^{57}\text{Ni} \rightarrow ^{57}\text{Co} \rightarrow ^{57}\text{Fe} \) (Clayton 1974). The decay produces γ-ray lines with average energy per decay \( \sim 1.7 \text{ MeV} \) (\( ^{56}\text{Ni} \) decay with an e-folding time of 8.8 days) or \( \sim 3.6 \text{ MeV} \) (\( ^{56}\text{Co} \) decay with an e-folding time of 113.7 days). These line γ-rays are degraded in their paths through the SN ejecta, predominantly by Compton scatterings (see, e.g., Cassé & Lehoucq 1994 for a review). Nonthermal electrons produced at the sites of scattering and other processes (pair production and photoelectric absorption) heat the ejecta, yielding thermal emissions at optical and NIR wavelengths.

The γ-ray emissions from SNe provide a unique tool for studying the amount and distribution of the predominant radioactive isotope \( ^{56}\text{Co} \) (therefore \( ^{56}\text{Ni} \) produced at the explosion). Density structure in the SN ejecta could also be inferred by modeling line profiles that are affected by Compton scatterings. For example, unexpectedly early detections of the high-energy emission from SN 1987A (Dotani et al. 1987; Sunyaev et al. 1987; Matz et al. 1988) revealed the important role of Rayleigh-Taylor instability and mixing in the SN ejecta (e.g., Chevalier 1976; Hachisu et al. 1990). This example highlights the great importance of modeling and analyzing γ-ray emission from SNe. Except for the very nearby SN 1987A, unfortunately there are to date only a few other examples of possible detection of γ-rays from the \( ^{56}\text{Ni} \) decay chain from SNe: one marginal detection (SN Ia 1991T; Lichte et al. 1994; Morris et al. 1997) and two upper limits (SNe Ia 1986G and 1989bu; Matz & Share 1990; Leising et al. 1999). However, now that the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) has been launched and some new γ-ray observatories are being planned (e.g., Takahashi et al. 2001), it is important to make predictions about γ-ray emissions (spectra and light curves), taking into account recent developments in SN research, i.e., multidimensionality (see, e.g., Maeda et al. 2006 and references therein).

Most studies on γ-ray transport in SN ejecta have been restricted to one-dimensional, spherical models. Recently, a few three-dimensional γ-ray transport computations for SNe have become available: Höflich (2002) has developed a three-dimensional γ-ray transport computational code and applied it to a three-dimensional hydrodynamic model of a Type Ia supernova (Khokhlov 2000). Hungerford et al. (2003) has also developed a three-dimensional γ-ray transfer code. They computed γ-ray spectra for three-dimensional asymmetric (bipolar) Type II supernova models and did the same later for three-dimensional single-lobe explosion models (Hungerford et al. 2005).

Given the higher density and smaller \( ^{56}\text{Ni} \) mass for core-collapse supernovae than SNe Ia, there is no doubt that core-collapse SNe are more difficult to detect in the high-energy range (e.g., Timmes & Woosley 1997). For example, Höflich et al. (1998) predicted the detection limit of SNe Ia by \textit{INTEGRAL} to be \( \sim 10 \text{ Mpc} \) (\( \sim 3 \text{ yr}^{-1} \)), while Hungerford et al. (2003) estimated that for SNe II (more or less similar to SN 1987A) to be \( \sim 650 \text{ kpc} \) (\( \sim 1 - 2 \text{ per 100 yr} \)). Accordingly, the number of theoretical predictions of hard X-ray and γ-ray emission from core-collapse SNe is still small to date, except models for the very nearby SN 1987A (e.g., McCray et al. 1987; Woosley et al. 1987; Shibazaki & Ebisuzaki 1988; Kunigami et al. 1989). Despite this, in view of the proposed large asymmetry in core-collapse SNe (see, e.g., Maeda & Nomoto 2003 and references therein) and its possible direct relation to high-energy emissions, the theoretical prediction of high-energy emission for a variety of core-collapse SN models is important in order to uncover the still-unclarified nature of the
explosion and understand trends that may be possible to observe with current and future instruments.

In this respect, potentially interesting targets among core-collapse SNe include very energetic SNe, often called “hypernovae” (Iwamoto et al. 1998). A prototypical hypernova is SN 1998bw, discovered in association with the γ-ray burst GRB 980425 (Galama et al. 1998). Its broad absorption features in optical spectra around maximum brightness and very bright peak magnitude led Iwamoto et al. (1998), assuming spherical symmetry, to conclude that the kinetic energy \( E_{51} \equiv E_k / 10^{51} \) ergs \( \sim 30 \), the ejecta mass \( M_E \sim 10 \ M_\odot \), the main-sequence mass \( M_{\text{MS}} \sim 40 \ M_\odot \), and the mass of newly synthesized radioactivity \( M_r \) \((^{56}\text{Ni}) \sim 0.6 \ M_\odot \) (see also Woosley et al. 1999). Following this and motivated by the deviation between the spherical hypernova model prediction and observations after \( \sim 100 \) days, Maeda et al. (2002a, 2006b) have presented a comprehensive study comparing various observations of SN 1998bw with theoretical expectations from jetlike aspherical explosion models of Maeda et al. (2002), using multidimensional radiation transport calculations. They found that an aspherical model with \( E_{51} \sim 20 \) consistently provides a good reproduction of optical emission from the explosion to \( \gtrsim 1 \) yr.

This paper follows the analysis of optical emission from aspherical hypernovae applied to SN 1998bw by Maeda et al. (2006a). In this paper we present theoretical predictions of high-energy emission from the same set of aspherical hypernova models as presented in Maeda et al. (2002, 2006a, 2006b). Because the models are intrinsically aspherical, we make use of fully three-dimensional hard X- and γ-ray transport computations. In § 2, details of the computational method are presented with a brief summary of the input models. In § 3, the overall synthetic spectra are presented. Section 4 focuses on line profiles. In § 5, light curves of some lines are presented.

In addition to modeling high-energy emission from SN 1998bw-like hypernovae, also interesting is the applicability of a gray effective absorptive opacity for γ-ray transport, which is often used as an approximation in computations of optical spectra and light curves of SNe to save computational time (e.g., Sutherland & Wheeler 1984). Although it has been examined in one-dimensional spherically symmetric cases with the conclusion that the approximation is good if an appropriate value is used for the effective γ-ray opacity, it has not yet been examined whether this is also the case for aspherical models. In § 6, the applicability of the gray absorptive γ-ray opacity for (jetlike) aspherical models is examined by comparing results with detailed γ-ray transport and with gray transport. Finally, in § 7 conclusions and discussion, including an estimate of the detectability of the high-energy emission, are presented.

2. METHOD AND MODELS

2.1. Method

We have developed a fully three-dimensional, energy-dependent, and time-dependent γ-ray transport computational code. It has been developed following the individual packet method using a Monte Carlo scheme as suggested by Lucy (2005). The code follows γ-ray transport in SN ejecta discretized in three-dimensional Cartesian grids \((x_i, y_j, z_k)\) (linearly discretized) and in time steps \( (t_n) \) (logarithmically discretized). For the ejecta dynamics, we assume homologous expansion, which should be a good approximation for SNe Ia/IIb/IC. The density at time interval \( (t_n, t_{n+1}) \) is assumed to be homogeneous in each spatial zone with the value at time \( t_{n+1/2} \equiv \left( t_n t_{n+1} \right)^{1/2} \).

The transport is solved in the SN rest frame. The expansion of the ejecta is taken into account as follows. First, cross sections for interactions with SN materials given in the comoving frame are transformed into the rest frame (Castor 1972). The fate of a photon is then determined in the rest frame. If a packet survives as high-energy photons after the interaction, the new direction and the energy are given at the comoving frame, depending on the specific interaction taking place (see below). The direction and the energy are then converted to the SN rest frame (Castor 1972).

Gamma-ray lines from the decay chains \( ^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe} \) and \( ^{57}\text{Ni} \rightarrow ^{57}\text{Co} \rightarrow ^{57}\text{Fe} \) are included. The numbers of lines included in the computation are \( 6 \) \((^{56}\text{Ni} \) decay), \( 24 \) \((^{56}\text{Co} \), \( 4 \) \((^{57}\text{Ni} \), and \( 3 \) \((^{57}\text{Co} \) (Lederer & Shirley 1978, p. 160; Ambwani & Sutherland 1988). In the present study we focus on the \( ^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe} \) chain, which includes the 812 keV \((^{56}\text{Ni} \), 847 keV \((^{56}\text{Co} \), and 1238 keV \((^{56}\text{Co} \) lines.

For the interactions of γ-rays with SN materials, we consider pair production, Compton scattering, and photoelectric absorption. For pair production, cross sections are adopted from Hubbell (1969; see also Ambwani & Sutherland 1988). For Compton scattering, the Klein-Nishina cross section is used. For photoelectric absorption, cross sections compiled by Höflich et al. (1992) from Veigele (1973) are used.

If an interaction takes place, the fate of the γ-ray packet is chosen randomly in proportion to the cross section of each possible interaction. If pair production is its fate, an electron and a positron are created. For the electron path, the electron deposits the entire energy to the ejecta. For the positron path, the positron annihilates with an ambient electron, producing two γ-rays (assuming no positronium formation). The positron kinetic energy is deposited to the thermal pool. These processes are assumed to take place in situ. According to this prescription, a packet either becomes the 511 keV γ-ray lines or is absorbed. Its fate is selected randomly in proportion to the branching probability depending on the initial photon energy before the pair production. If Compton scattering is its fate, the polar angle of the scattering relative to the incoming photon direction in the comoving frame is randomly sampled according to the Klein-Nishina distribution using a standard Monte Carlo rejection technique (the Kahn method). The azimuthal angle is randomly selected in the comoving frame. The packet is now either a γ-ray packet or a nonthermal electron packet (assumed to deposit its entire energy to the SN ejecta immediately), determined randomly according to the energy flowing into each branch. If photoelectric absorption is its fate, the entire energy of the packet is absorbed. Possible X-ray fluorescence photons are not followed in the present simulations, but these photons are below the low-energy cutoff, having negligible effects on the energy range examined in this paper.

For a time-advancing scheme, the code has two options: The first is exact time advancing, taking into account the time interval at each photon flight. The other is no time advancing, assuming that the flight time through the ejecta is negligible. In this work, we use exact time advancing for computations of γ-ray light curves (and for computations of optical emission in Maeda et al. 2006a) and no time advancing for computations of spectra. This is in order to optimize the number of photons escaping at a given time interval in the spectral computations, since the computation of spectra with fine energy bins already requires a large number of packets and large computational time. For γ-rays, the negligible time delay approximation is a good one. We have confirmed this for the present models by performing the fully time-dependent computation but with the number of packets entering each time...
interval smaller than used in the standard no–time-advancing spectrum computations.

In view of the recent investigation by Milne et al. (2004) that concluded that not all the published one-dimensional $\gamma$-ray transport codes give mutually consistent results, we test the capability of our new code by computing $\gamma$-ray spectra based on the (spherical) SN Ia model W7 (Nomoto et al. 1984), for which many previous studies are available for comparison. We have compared our synthetic $\gamma$-ray spectra at 25 and 50 days with Figure 5 of Milne et al. (2004). We found excellent agreement between our results and the spectra resulting from a majority of previous codes, e.g., that of Hungerford et al. (2003).

In this study, the ejecta are mapped onto $60^3$ Cartesian grids. For spectrum synthesis, $1.5 \times 10^8$ photon packets with equal initial energy content are used. In escaping the ejecta, these packets are binned into 10 angular zones with equal solid angle from $\theta = 0^\circ$ to $180^\circ$ (here $\theta$ is the polar angle from the z-axis) and into 3000 energy bins up to 3 MeV with equal energy interval of 1 keV. For the $\gamma$-ray light curve computations, $10^8$ photon packets are used. In escaping the ejecta, the packets are binned into 36 time steps logarithmically spaced from day 5 to day 300, as well as into the angular and energy bins.

2.2. Models

Input models for the $\gamma$-ray transport computations are taken from the aspherical model A and the spherical model F from Maeda et al. (2006a). Model A is the result of a jetlike explosion with the initial energy input at the collapsing core injected more in the z-axis than in the r-axis (see Maeda et al. 2002 for details). In Maeda et al. (2006a, 2006b), we examined optical light curves ($\lesssim$500 days), as well as expected optical spectral characteristics in both early ($\lesssim100$ days) and late ($\gtrsim100$ days) phases. The structure of model A at homologous expansion phases is shown in Figure 1.

In this study, we examine the following models: $(M_{\text{ej}}/M_\odot, E_{51}, M(56\text{Ni})/M_\odot) = (10.4, 10, 0.31)$ and $(10.4, 20, 0.39)$ for model A and $(10.4, 10, 0.28)$ and $(10.4, 50, 0.40)$ for model F [hereafter $M_{\text{ej}}$ is the ejecta mass, $E_{51}$ is the kinetic energy of the expansion in units of $10^{51}$ ergs, and $M(56\text{Ni})$ is the mass of $56\text{Ni}$ synthesized at the explosion]. Maeda et al. (2006a) concluded that the optical properties of SN 1998bw are explained consistently by model A with an energy $E_{51} \sim 20$ and with $M(56\text{Ni}) \sim 0.4 M_\odot$, so we regard model A as representing a prototypical hypernova.

As seen in Figure 1, model A is characterized by concentration of the $56\text{Ni}$ distribution along the z-axis, which is a consequence of the explosive nucleosynthesis in jetlike aspherical explosions (Nagataki 2000; Maeda et al. 2002; Maeda & Nomoto 2003). Because $56\text{Ni}$ is the source of $\gamma$-rays, the distribution will sensitively affect the $\gamma$-ray transport and resulting hard X- and $\gamma$-ray emission. Figure 2 shows the distribution of $56\text{Ni}$ along the line of sight for our models. The amount of $56\text{Ni}$ is integrated in the plane perpendicular to the line of sight within the constant line-of-sight velocity interval. Thus, Figure 2 shows a profile of $\gamma$-ray lines from the decay of $56\text{Ni}$ or $56\text{Co}$ in the optically thin limit.
Figure 2 shows that model A yields $^{56}$Ni at high velocities if it is viewed from the polar ($z$) direction. On the other hand, if it is viewed from the equatorial ($r$) direction, it yields a distribution that is sharply peaked at zero and low velocities. Note that model A with $E_{51} = 20$ shows $^{56}$Ni at velocities higher than those in model F with $E_{51} = 50$.

3. HARD X- AND $\gamma$-RAY SPECTRA

Figures 3 and 4 show synthetic $\gamma$- and hard X-ray spectra at 25 days after the explosion. Figures 5 and 6 show those at 50 days after the explosion. Thanks to the large $E_K/M_{ej}$ as compared to (normal) SNe II and to the absence of a massive hydrogen layer, the emergence of the high-energy emission is much earlier for these models (on the order of 1 month) than for SNe II (on the order of 1 yr).

An aspherical model yields the emergence of the high-energy emission earlier than a spherical model with the same energy: at 25 days, model A with $E_{51} = 10$ already shows up at high energy, although model F with $E_{51} = 10$ does not show up. Indeed, the former, despite the energy $E_{51} = 10$, gives a date of emergence comparable to that of model F with $E_{51} = 50$. The timescale of the $\gamma$-ray emission is discussed further in § 5.

Model A is characterized by a large line-to-continuum ratio, especially early on (Fig. 3). Because the continuum is formed by the degradation of line photons by Compton scatterings, a large line-to-continuum ratio is realized for the plasma with a low optical depth for Compton scatterings. Indeed, $\gamma$-ray transport computations typically predict a larger ratio at more advanced epochs (see, e.g., Sunyaev et al. 1990). This is also seen by comparing model F with different energies ($E_{51} = 10, 50$) at day 50.
(Fig. 5): the larger energy leads to smaller optical depth and therefore to a larger line-to-continuum ratio. At 25 days, model A with either $E_{51} = 20$ or 10 yields a ratio larger than that of model F with $E_{51} = 50$, which is attributed to the existence of high-velocity $^{56}\text{Ni}$ at low optical depth in model A (Figs. 1 and 2). At 50 days, the effect becomes less significant (i.e., the ratio becomes comparable for model A [$E_{51} = 10$ or 20] and for model F with $E_{51} = 50$) but still visible as compared with model F with $E_{51} = 10$ (Fig. 5).

Another feature is seen in hard X-ray spectra. Model A has the hard X-ray cutoff at higher energy than model F (Figs. 4 and 6). The cutoff is formed by photoelectric absorption, which is dependent on metal content (e.g., Grebenev & Sunyaev 1987). At 25 days, only the emission near the surface (along the $z$-axis for model A) can escape the ejecta. The cutoff is therefore determined by metal content near the surface. In model F, the surface layer is dominated by intermediate-mass elements (i.e., the CO core of the progenitor star). On the other hand, in model A the emitting region contains a large fraction of Fe-peak elements, most noticeably $^{56}\text{Ni}$ (or Co, Fe). Therefore, the photoelectric cutoff should be at a higher energy in model A than in model F. At more advanced epochs, an observer looks into deeper regions. Then the contribution from the deeper region becomes bigger and bigger, yielding an increase of the cutoff energy in model F, since $^{56}\text{Ni}$ is centrally concentrated (Fig. 2). This effect is also seen in model A, but to a smaller extent. Although the mass of $^{56}\text{Ni}$ within a given velocity interval also increases toward the center (except the innermost region where the $^{56}\text{Ni}$ fraction is very small) in model A along the $z$-axis, the increase is less dramatic than in model F (e.g., compare the masses of $^{56}\text{Ni}$ at

Fig. 4.—Same as Fig. 3, but with the horizontal axis in logarithmic scale, for presentation of the hard X-ray spectra.
In the above discussion on the photoelectric absorption, one would expect to use the $^{56}\text{Ni}$ distribution along the "$r$-axis," not the $z$-axis, for the observer at the $r$-axis. However, this is not the case. As discussed by Hungerford et al. (2003, 2005), even for an observer at the $r$-axis, the $^{56}\text{Ni}$ contributing most of the emission is that at the $z$-axis, i.e., an observer at the $r$-axis looks at the emitting polar $^{56}\text{Ni}$ blobs sideways (see also Maeda et al. 2006a). To clarify this, in Figure 7 we show the last scattering points of hard X- and $\gamma$-rays. Also shown are contours of the optical depth for observers at the $+z$- and $+r$-directions. An observer at the $z$-axis looks at an emitting blob moving toward the observer, while an observer on the $r$-plane looks at a pair of emitting blobs sideways.

This is further discussed in §4 and 5, but here we point out one way that the effects of the viewing angle differ between our model and that of Hungerford et al. (2003). Their models do not yield a large difference in the absolute flux, while our models do show a boost of the high-energy luminosity toward the $z$-axis. A similar behavior is also seen in optical emission in our models (Maeda et al. 2006a). The mechanism of the boost should be the same as that for optical photons. Initially, at high density only the sector-shaped region along the $z$-axis can yield escaping photons (Fig. 7). The cross-sectional area of this photosphere is larger toward the $z$-axis than the $r$-axis, making the luminosity increase toward the $z$-axis. As time goes by, the ejecta optical depth decreases, and therefore the photosphere moves to cover the equatorial region. The difference becomes less and less significant, as seen by comparing Figures 3 and 5. The different behavior is probably due to the different degree of penetration.

20,000 and 10,000 km s$^{-1}$ for model A in Fig. 2). Therefore, the metal content of the emitting region does not temporally evolve very much in model A.
of \(^{56}\text{Ni}\) into the outer layers. Hungerford et al. (2003, 2005) presented SN II models with a massive hydrogen envelope, which does not exist in our model SNe Ib/c. The existence of the hydrogen envelope generally yields a less aspherical distribution of \(^{56}\text{Ni}\) and the emitting region in SNe II than in SNe Ib/c (e.g., Wang et al. 2001). In any case, as Hungerford et al. (2005) have suggested, the high-energy emission can very sensitively depend on the type and degree of asymmetry; therefore, transport calculations are very important.

4. LINE PROFILES

We now turn our attention to line profiles. Figure 8 shows line profiles of the \(^{56}\text{Ni}\) 812 keV and \(^{56}\text{Co}\) 847 keV lines at 25 days. Figure 9 shows the \(^{56}\text{Co}\) 1238 keV line. Figures 10 and 11 show the same lines at 50 days. At these early epochs, the ejecta are not thin to high-energy photons (Fig. 7), and therefore the line profiles are different from those expected in the optically thin limit (Fig. 2).

At day 25, an observer only sees the region near the surface (Fig. 7). For model A, the region is further concentrated along the \(z\)-axis (the top of the \(^{56}\text{Ni}\) bubble” in Fig. 1). Figures 8 and 9 show that the line profiles are very asymmetric, showing only the emission at the blue coming from the region moving toward an observer, except an observer at the \(r\)-axis. For an observer at the \(r\)-axis, even the emission at the rest wavelength is seen, which is especially evident for the more energetic, and therefore less optically thick, model (model A with \(E_{51} = 20\)). The emitting region is now at the outer edge(s) of the \(^{56}\text{Ni}\) distribution, and the density is relatively small there (Fig. 1). The line of sight, connecting the emitting region(s) and an observer at the \(r\)-direction, passes only through the low-density region, including the region moving away from the observer. On the other
hand, the line of sight for an observer at the z-axis passes through the dense, central region. For example, this behavior is seen in Figure 7 by comparing the regions having an optical depth $\tau < 10$ at day 25, for the observers at the z- and r-axes. For the observer at the $+z$-direction, the region contains only the emitting blob moving toward the observer. For the observer at the $+r$-direction, on the other hand, a pair of the emitting blobs along the z-axis, seen from the side by the observer, are included in the regions with $\tau < 10$.

At 50 days, the line broadens redward as a photon even from the far side escapes the ejecta more easily because of decreasing density. Still, only the blue part is seen for an observer at the z-direction (Figs. 10 and 11). This is in contrast to model F with $E_{51} = 50$, which now shows the emission at the rest wavelength. It is interesting to see that the line profiles of model A (either $E_{51} = 10$ or 20) viewed at the z-direction resemble the $^{56}\text{Ni}$ distribution in the hemisphere moving toward the observer (Fig. 2). This suggests that the photons from the far hemisphere are almost totally blocked by the high-density central region, while the $^{56}\text{Ni}$-rich region itself is nearly optically thin. This is indeed the case, as seen in Figure 7. For model A viewed at the $r$-direction and for model F, the line profile is explained by a continuously decreasing escape probability. These arguments imply that, assuming that we have a temporal series of $\gamma$-ray observations, the line profiles for model A viewed at the $z$-direction should show the time interval within which the line profiles are almost fixed, while model A viewed at the $r$-direction and model F should show continuous changes in the line profile until all the ejecta become optically thin. This could be an interesting observational target, since the temporally “fixed” line profile, if observed, suggests that the viewing angle is close to the pole. In this case, the line shape directly traces the distribution of $^{56}\text{Ni}$. 

Fig. 7.—Last scattering points of $\gamma$-ray and hard X-ray photons at 25, 50, 100, and 200 days since the explosion for model A with $E_{51} = 20$. Also shown are contours of optical depth for an observer at the z-axis (at $+z$-direction; solid lines) and at the r-axis (at $+r$-direction; dotted lines). The horizontal and vertical axes are the $V_x$ and $V_z$ axes, respectively. At 25 days, contours are shown for optical depths $\tau = 1, 10,$ and 30, while for other epochs they are shown only for $\tau = 1$. The optical depth for the contours is computed assuming an opacity equal to $\frac{1}{3}$ of the Thomson cross section.
In addition, line profiles, sensitively dependent on the viewing angle, as well as the degree of asphericity, could be used as a tracer of the distribution of $^{56}$Ni and density once $\gamma$-ray observations at \~1 MeV with sufficient sensitivity become possible. The detectability is discussed in § 7.

5. LIGHT CURVES

Figure 12 shows light curves of the $^{56}$Ni 812, $^{56}$Co 847, and $^{56}$Co 1238 keV lines at a distance of 10 Mpc. For the 1238 keV line, the flux is computed by integrating a spectrum in the 1150–1340 keV range. For the 812 and 847 keV lines, the sum of the fluxes is computed by first integrating a spectrum in the 800–920 keV range; then the individual contribution is computed with the decay probability at the corresponding epochs assuming that the escape fractions for these two lines are equal. The assumption of equal escape fractions should be a good approximation, since these two lines are close in energy, yielding almost identical Compton cross sections (see also Milne et al. 2004).

Model A shows the emergence of the $\gamma$-rays earlier, even though the energy is smaller, than model F. This is due to the large amount of $^{56}$Ni at low-density and high-velocity regions. Later on, the $\gamma$-rays become stronger for model F with $E_{51} = 50$ than for model A ($E_{51} = 10, 20$). Three effects are responsible: (1) The contribution of the dense central region stopping the photons becomes large. (2) The overall optical depth $\tau \propto M^2/E$ is larger for model A than for model F. (3) Model F with $E_{51} = 50$ has a bit large $M(^{56}$Ni) as compared to model A. Because of this temporal behavior, the enhancement of $\gamma$-ray flux is more noticeable for the $^{56}$Ni line (with an $e$-folding time of 8.8 days) than for the $^{56}$Co lines (with an $e$-folding time of 113.7 days).

As discussed in § 3, the effect of the viewing angle is seen at early epochs. Model A emits more toward the z-direction than the
$r$-direction. This behavior is qualitatively similar to that in optical emission (Maeda et al. 2006a). The effect virtually vanishes around $\sim 100$ days for model A with $E_{51} = 20$, which is consistent with a rough estimate that the ejecta become optically thin to Compton scattering at $\sim (\tau_0)^{1/2} \sim [1250(M_0/M_\odot)^2/E_{51}]^{1/2} \sim 80$ days (see, e.g., Maeda et al. 2003; see also Fig. 7), where $\tau_0$ is the optical depth to Compton scattering at day 1. In the above estimate, the cross section is assumed to be $\frac{1}{6}$ of the Thomson scattering cross section, and the composition $Y_e = 0.5$.

6. COMPARISON BETWEEN DETAILED AND GRAY TRANSPORT

In previous sections, we presented model predictions for high-energy spectra and light curves. However, $\gamma$-ray transport in the SN ejecta has another role that is as important as the high-energy emission itself: the $\gamma$-rays cause heating of the ejecta; i.e., non-thermal electrons scattered off ions by Compton scattering rapidly pass their energies to thermal particles through ionization, excitation, and scattering with thermal electrons. The thermal energy is then converted to optical photons. In this way, the energy lost from the high-energy photons determines the optical luminosity from a supernova. In this section, we examine how much energy is stored in the ejecta.

In Maeda et al. (2006a), we made use of detailed three-dimensional high-energy photon transport to compute optical light curves and nebular spectra of models A and F (and other models). On the other hand, a gray effective absorptive assumption for $\gamma$-ray transport has been frequently used for computations of $\gamma$-ray deposition and optical light curves. Sometimes it has been used, although in spherically symmetric models, to compute optical light curves for (hypothetical) non–spherically symmetric SNe (e.g., Folatelli et al. 2006; Tominaga et al. 2005). It is therefore
important to examine the applicability of the assumption for aspherical SNe.

Figure 13 shows synthetic optical light curves for models A and F. Results with the detailed three-dimensional transport and with the simplified gray absorptive $\gamma$-ray opacity (with various effective opacity $\kappa_\gamma$) are compared. Figure 13 shows that the gray absorptive approximation is actually good for computations of $\gamma$-ray deposition, and thus for computations of optical light curves, if an appropriate value is used for the effective opacity. With the value $\kappa_\gamma = 0.027 \text{ cm}^2 \text{ g}^{-1}$, we obtain optical light curves for both the spherical model F and the aspherical model A almost identical to those obtained with the detailed $\gamma$-ray transport computations.

At late epochs \( \gtrsim 100 \)–\( 200 \) days (depending on models) the ejecta become optically thin to $\gamma$-rays. At these epochs, $\gamma$-rays suffer at most only one Compton scattering before escaping the ejecta. In this idealized situation, the “effective” $\gamma$-ray opacity can be computed by taking an appropriate average of the Klein-Nishina cross section for various scattering angles and $\gamma$-ray line energies. In this way, Sutherland & Wheeler (1984) yield $\kappa_\gamma = 0.022 \text{ cm}^2 \text{ g}^{-1}$ assuming the typical line energy $\sim 2 \text{ MeV}$. This value is dependent on the line list. We have also performed the estimate of the effective opacity in the optically thin limit under the condition that the averaged absorbed energy per photon flight is equal for the detailed case and for the effective absorption case and found that for the $^{56}$Co lines, $\kappa_\gamma = 5.08 (Z/A) \text{ cm}^2 \text{ g}^{-1}$. This yields $\kappa_\gamma \sim 0.025 \text{ cm}^2 \text{ g}^{-1}$ for the SNe Ib/c composition. Indeed, Figure 13 implies that this value is probably even better than $0.027 \text{ cm}^2 \text{ g}^{-1}$ in the late phase, although the difference is small. We emphasize that in this situation, the effective opacity is independent from the geometry of the ejecta. This is confirmed, although not generally, by the fact that the $\kappa_\gamma = 0.027 \text{ cm}^2 \text{ g}^{-1}$.
reproduces the light curve obtained by the detailed computations for both models A and F.

Somewhat surprising is that (1) the same value $\kappa_{\gamma} = 0.027 \text{ cm}^2 \text{ g}^{-1}$ reproduces the detailed transport computations rather well at early epochs and (2) this applies not only to the spherical model but also to the aspherical model. Because multiple scatterings take place, now the effective $\kappa_{\gamma}$-ray opacity can be geometry- and time-dependent and can be different from the value at the late phases. For example, Sutherland & Wheeler (1984) suggested $\kappa_{\gamma} = 0.03 \text{ cm}^2 \text{ g}^{-1}$ taking account multiple scatterings. Fransson (1994) gave the value $\kappa_{\gamma} = 0.03 \text{ cm}^2 \text{ g}^{-1}$ with $Y_e = 0.5$ from a series of Monte Carlo simulations. Colgate et al. (1980) gave the value $\kappa_{\gamma} = 0.028 \text{ cm}^2 \text{ g}^{-1}$. These authors used different ejecta models. The small differences among these studies (although there are some exceptions, e.g., $0.07 \text{ cm}^2 \text{ g}^{-1}$ by Woosley et al. 1986) suggest that the effects of density and $^{56}\text{Ni}$ distribution on the total deposition rate are small (in the spherically symmetric case). The present study suggests that this is also the case even in asymmetric cases.

7. CONCLUSIONS AND DISCUSSION

In this paper, we first reported the development of a new code for three-dimensional computations of hard X-ray and $\gamma$-ray emission resulting from radioactive decays in supernovae. The code is useful for solving many problems. Among them is the applicability of a gray absorptive approximation in SN ejecta without spherical symmetry. We have shown, although only for some specific models, that this is actually a good approximation. This approximation has been extensively used even in analyzing SNe with hypothetical asymmetry (e.g., Folatelli et al. 2006; Tominaga et al. 2005), and we have confirmed its applicability using three-dimensional computations.
Irrespective of the direction to the observer, the aspherical models yield (1) early emergence of the high-energy emission, and therefore the large peak flux, (2) large line-to-continuum ratio, and (3) large cutoff energy in the hard X-ray band as compared to spherical models. These are qualitatively similar to what are expected from extensive mixing of $^{56}\text{Ni}$ (see, e.g., Cassé & Lehoucq 1994) by, e.g., Rayleigh-Taylor instability (e.g., Hachisu et al. 1990). However, the degree of $^{56}\text{Ni}$ penetration is more extreme, and therefore the effects of $^{56}\text{Ni}$ mixing are more noticeable, in our models than in spherical mixing cases. For example, for model A, the cutoff energy (by photoelectric absorption) is already at $\sim 100$ keV at the emergence of the $\gamma$-rays, and it does not temporally evolve very much because the mass fraction of $^{56}\text{Ni}$ (Co) does not increase very much toward the center along the $z$-axis. This constant cutoff energy would be useful to distinguish the aspherical models from spherical ones once we have a sequence of hard X-ray observations.

Another interesting result is that line profiles are sensitively dependent on asphericity, as well as direction to the observer. Lines should show a larger amount of blueshift for an observer closer to the polar ($z$) direction. For an observer at the equatorial ($r$) direction, lines show emission at the rest wavelength even at very early epochs. These results are not expected in spherically symmetric models. Although analysis of line profiles will require future observatories with very high sensitivity (e.g., Takahashi et al. 2001) and/or a supernova very nearby, once it becomes possible, then it will be extremely useful to trace the asphericity and energy and therefore the explosion mechanism of SNe.

For example, a possibly interesting observational strategy is implied. In model A the $^{56}\text{Ni}$ region becomes optically thin at a rather early phase when the inner regions are still optically thick. This leads to the following temporal evolution for an observer at the $z$-direction. First, the line becomes redder and redder with time. Then at some epoch it stops changing shape very much, closely presenting the $^{56}\text{Ni}$ distribution in the hemisphere moving toward the observer. Finally, the line from the other hemisphere appears. This evolution is unique as compared with spherical models or for an observer at the $r$-direction, either of which should show continuous reddening until all the ejecta become optically thin.

Because we show that some features of the aspherical models depend on the degree of asphericity but not on the direction to the observer, while the others depend on both the asphericity and the direction, a combination of various analyses will be helpful to distinguish models and direction to the observers. A problem is, of course, how many hypernovae are expected to be able to be observed with current and future observatories. For the aspherical model A with $E_{51} = 20$, the expected maximum line fluxes are about half of those of typical SN Ia models. The less energetic model ($E_{51} = 10$) yields even smaller fluxes. This is because of a smaller amount of $^{56}\text{Ni}$ and a larger ratio $M^2/E_K$ (and therefore later emergence of the radioactive decay lines) than in the SN Ia models. Even worse, the rate of occurrence is much smaller for hypernovae than for SNe Ia. In this respect, there is no doubt that SNe Ia are the most promising targets in radioactive $\gamma$-rays.

However, hypernovae could still be interesting targets in $\gamma$-rays among core-collapse SNe. Taking SN 1987A as a typical SN II, its peak 847 keV line flux was $\sim 10^{-7}$ photons cm$^{-2}$ s$^{-1}$, yielding $\sim 3 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ if it were at 10 Mpc. Our aspherical hypernova models predict a peak flux more than 2 orders of magnitude larger than this. Therefore, for a given instrument sensitivity, it is visible at least 1 order of magnitude farther than a typical SN II. Low-mass SNe Ib/c should also be discussed. Although the nature of the SNe Ib/c seems very

With the code, we have presented predictions of hard X-ray and $\gamma$-ray emission in aspherical hypernova models. The models were verified by fitting optical properties of the prototypical hypernova SN 1998bw (Maeda et al. 2006a, 2006b); therefore, we regard the model prediction as being based on “realistic” hypernovae.

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**Fig. 12.** Light curves of (a) the $^{56}\text{Ni}$ 812 keV line, (b) the $^{56}\text{Co}$ 847 keV line, and (c) the $^{55}\text{Co}$ 1238 keV line at the reference distance 10 Mpc. For the 812 and 847 keV lines, the flux is computed by integrating a spectrum in the 800–920 keV energy range and then assuming that the escape fractions for these two lines are equal. For the 1238 keV line, the flux is computed by integrating a spectrum in the 1150–1340 keV energy range. Shown here are model A with $E_{51} = 20$ (thick black curves) and 10 (thin black curves) and model F with $E_{51} = 50$ (thick gray curves) and 10 (thin gray curves). For model A, the flux is shown for the $z$-direction (solid curves) and the $r$-direction (dotted curves), as well as the angle-averaged direction (dashed curves).
heterogeneous, let us assume that $M_\odot = 2 M_\odot$, $E_{51} = 1$, and $M(56\text{Ni}) = 0.07 M_\odot$. These values give a $\gamma$-ray escape timescale comparable to that of the present models (see § 5), resulting in an estimate of the peak line flux $\sim 5$ times smaller than for the present models. For the sensitivity of INTEGRAL (3 $\sigma$ in 10$^8$ s), we estimate that the maximum distances within which $\gamma$-rays are detectable are $\sim 500$ kpc, 4 Mpc, and 7 Mpc for SNe II, SNe Ib/c, and hypernovae, respectively (here we assume a line width of 10, 20, and 40 keV for SNe II, SNe Ib/c, and hypernovae, respectively). The latter two, especially the detection limit for hypernovae, cover some starburst galaxies such as M82 ($\sim 4$ Mpc). Since SN 1987A, the nearest SNe for each type have been SN II 2004dj ($\sim 3$ Mpc), SN Ic 1994I ($\sim 7$ Mpc), and the hypernova (but weaker than SN 1998bw) SN Ic 2002ap ($\sim 10$ Mpc). The prototypical hypernova SN 1998bw was at $\sim 36$ Mpc. Therefore, the sensitivity of INTEGRAL is unfortunately not enough to detect these core-collapse SNe, and we will have to wait for next-generation hard X- and $\gamma$-ray telescopes. If these telescopes are designed to achieve a sensitivity better than that of INTEGRAL by 2 orders of magnitude (see, e.g., Takahashi et al. 2001), then the maximum distances are 5, 40, and 70 Mpc for SNe II, SNe Ib/c, and hypernovae, respectively. The detection limits for SNe Ib/c then cover some clusters of galaxies such as Virgo ($\sim 18$ Mpc), Fornax ($\sim 18$ Mpc), and even Hydra ($\sim 40$ Mpc). This sensitivity will lead to a comprehensive study of $\gamma$-ray emission, and therefore of explosive nucleosynthesis, in core-collapse SNe.

The observed rate of occurrence is $\sim 7 \times 10^{-3}$ and $\sim 1 \times 10^{-3}$ yr$^{-1}$ in an average galaxy for SNe II and SN Ib/c, respectively. The hypernova rate is rather uncertain. Podsiadlowski et al. (2004) gave a conservative estimate of the rate of $\sim 10^{-5}$ yr$^{-1}$. These values give, by multiplying the rate and the detectable volume, an observed probability of $\sim 1$ (SNe II): 70 (SNe Ib/c, but not hypernovae): 4 (hypernovae) for a given detector. The difference between the usual SNe Ib/c and hypernovae may (probably) be even smaller, since the estimate of SN Ib/c flux above is probably an upper limit (i.e., $M_\odot = 2 M_\odot$ seems to be almost a lower limit) and the hypernova rate is possibly an underestimate.

In sum, as far as detectability is concerned, a hypernova is worse than (usual) SNe Ib/c but potentially better than SNe II. Another question is whether any asphericity similar to that derived for the prototypical hypernova SN 1998bw (Maeda et al. 2006a, 2006b) exists in (usual) SNe Ib/c. If it does, as suggested by, e.g., Wang et al. (2001), then most of the properties shown in this paper should also apply for hard X- and $\gamma$-ray emission from these SNe Ib/c (since the timescale is similar to that of hypernovae; see § 5). One should of course take into account the fact that the expansion velocity and $M(56\text{Ni})$ are smaller than in hypernovae and ultimately require direct computations based on a variety of explosion models.

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