MULTICOLOR LIGHT CURVE SIMULATIONS OF POPULATION III CORE-COLLAPSE SUPERNOVAE: FROM SHOCK BREAKOUT TO $^{56}$CO DECAY

ALEXEY TOLSTOV$^{1}$, KEN’ICHI NOMOTO$^{1,6}$, NOZOMU TOMINAGA$^{2,1}$, MIHO N. ISHIKAKI$^{1}$, SERGEY BLINNIKOV$^{3,4,1}$, AND TOMOHARU SUZUKI$^{5}$

$^{1}$Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan; alexey.tolstov@ipmu.jp

$^{2}$Department of Physics, Faculty of Science and Engineering, Konan University, 8-9-1 Okamoto, Kobe, Hyogo 658-8501, Japan

$^{3}$Institute for Theoretical and Experimental Physics (ITEP), 117218 Moscow, Russia

$^{4}$All-Russia Research Institute of Automatics (VNIIA), 127055 Moscow, Russia

$^{5}$College of Engineering, Chubu University, 1200 Matsumoto-cho, Kasugai, Aichi 487-8501, Japan

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ABSTRACT

The properties of the first generation of stars and their supernova (SN) explosions remain unknown due to the lack of actual observations. Recently, many transient surveys have been conducted and the feasibility of detecting supernovae (SNe) of Pop III stars is growing. In this paper, we study the multicolor light curves for a number of metal-free core-collapse SN models (25–100 $M_\odot$) to determine the indicators for the detection and identification of first generation SNe. We use mixing-fallback supernova explosion models that explain the observed abundance patterns of metal-poor stars. Numerical calculations of the multicolor light curves are performed using the multigroup radiation hydrodynamic code STELLA. The calculated light curves of metal-free SNe are compared with non-zero-metallicity models and several observed SNe. We have found that the shock breakout characteristics, the evolution of the photosphere’s velocity, the luminosity, and the duration and color evolution of the plateau, that is, all of the SN phases from shock breakout to $^{56}$Co decay, are helpful for estimating the parameters of the SN progenitor: the mass, the radius, the explosion energy, and the metallicity. We conclude that the multicolor light curves could potentially be used to identify first-generation SNe in current (Subaru/HSC) and future transient surveys (LSST, James Webb Space Telescope). They are also suitable for identifying low-metallicity SNe in the nearby universe (PTF, Pan-STARRS, Gaia).

Key words: radiative transfer – shock waves – stars: abundances – stars: Population III – supernovae: general

1. INTRODUCTION

After the big bang, small density fluctuations and gravitational contraction lead to the formation of the first stars, called Population III stars (Pop III stars). Their formation initiated the baryonic evolution of the universe, e.g., the formation of the first galaxies and cosmic reionization. Their formation has been studied using cosmological simulations for a long time (e.g., Bromm & Yoshida 2011). However, their nature remains elusive. In particular, the initial mass function of the first stars, and thus the supernova (SN) explosions of the first stars, are still exciting issues (e.g., Hirano et al. 2014; Susa et al. 2014).

The nature of the first stars has mainly been studied using low-mass stars in the Galactic halo. These stars have a lifetime longer than the current age of the universe, and thus preserve the chemical abundance at the time of their formation. Such stars are referred to as metal-poor stars. With the goal of understanding the evolution of the early universe, many surveys of metal-poor stars have been conducted (e.g., Beers & Christlieb 2005) and follow-up high-dispersion spectroscopic observations have revealed their detailed abundance ratios (e.g., Cayrel et al. 2004; Yong et al. 2013). Metal-poor stars are classified by their Fe and C abundances, for example, metal-poor (MP) stars have [Fe/H] $<-1$, very metal-poor (VMP) stars have [Fe/H] $<-2$, extremely metal-poor stars (EMP) have [Fe/H] $<-3$, ultra metal-poor stars (UMP) have [Fe/H] $<-4$, hyper metal-poor stars (HMP) have [Fe/H] $<-5$, and carbon-enhanced metal-poor (CEMP) stars have [C/Fe] $>+1$. Observational studies of metal-poor stars show the larger fraction of CEMP stars at lower [Fe/H] (e.g., Hansen et al. 2014). In particular, all of the HMP stars show extremely high C abundance with [C/Fe] $>+3$.

Theoretical studies are required to derive the properties of the first stars from the abundance ratios of metal-poor stars (see Nomoto et al. 2013, for a review). Theoretical studies have clarified that the abundance patterns of the C-normal EMP stars are well reproduced by SN explosions with main-sequence masses $M_{\text{ms}}$ of $<100$ $M_\odot$ (Umeda & Nomoto 2002; Limongi et al. 2003; Tominaga et al. 2007b, 2014a; Heger & Woosley 2010). It is worth noting that there have been no clear signatures of pair-instability SNe with $M_{\text{ms}}$ of 140–300 $M_\odot$, although a hint of a star more massive than 300 $M_\odot$ was found in one metal-poor star with [Fe/H] $\sim -2.5$ (Aoki et al. 2014). For CEMP stars with s-process elements and [Fe/H] $>-3$, the abundance patterns of most CEMP stars are explained by the mass transfer from an AGB binary companion (e.g., Lugaro et al. 2012), and binary signatures have been found in their observations (Lucatello et al. 2005). For most of CEMP stars with [Fe/H] $<-3$ and for HMP stars, the C enhancements require faint SNe which eject a small mass of $^{56}$Ni as $M(^{56}\text{Ni}) = 10^{-2.01} M_\odot$ for CEMP stars and $M(^{56}\text{Ni}) < 10^{-3} M_\odot$ for HMP stars (e.g., Iwamoto et al. 2005; Heger & Woosley 2010; Ishigaki et al. 2014; Tominaga et al. 2014a). While analogies of faint SNe for CEMP stars have been detected recently (SN 1997D and SN 1999br, e.g., Zampieri et al. 2003, SN 2008ha, Valenti et al. 2009), the ejected $^{56}$Ni masses of the faint SN models for HMP stars are smaller than those estimated from light-curve analyses of nearby observed stars.
SNe (e.g., Smartt 2009). This could be due to the non-existence of such a faint SN in the present day or due to selection effect in the observations of nearby SNe.

On the other hand, observations of gas clouds by Fumagalli et al. (2011) suggest the presence of metal-free pockets at $z \sim 2$, and possible Pop III remnants at $z = 3.5$ are also observed (Crighton et al. 2015). Metal-free pockets provide more possibilities for the identification of SNe of Pop III stars (Pop III SNe). Furthermore, time-domain astronomy has recently attracted attention, and many transient surveys have been conducted (e.g., CRTS, Drake et al. 2009; PTF, Rau et al. 2009; ASSASN, Shappee et al. 2014; KISS, Morokuma et al. 2014) and additional studies are ongoing/planned with 8m class telescopes, e.g., Subaru/HSC (SHOOT, Tomimaga et al. 2014b) and LSST (Large Synoptic Survey Telescope). The feasibility of the detection of Pop III SNe is growing. Therefore, in order to distinguish these SNe from those of Population I or II stars, realistic predictions based on theoretical models and observations of the metal-poor stars are required.

In this paper, we present the light curves of a number of Pop III core-collapse SNe. Unlike similar numerical simulations performed by Whalen et al. (2013) and Smidt et al. (2014), we mostly concentrate on realistic SN models that reproduce the observed abundance patterns of metal-poor stars (Ishigaki et al. 2014). Our accurate consideration of radiative transfer allows us to determine the detailed shapes of multicolor light curves from the shock breakout epoch through $^{56}$Co decay. Detailed simulations of the light curves can be crucial for the detection and identification of Pop III SNe and this study provides fine points for current and future surveys.

The results of our simulations can also be used for finding and identifying low-metallicity SNe. The paper is organized as follows. In Section 2, we describe the mixing-fallback models and numerical methods used in our calculations. Section 3 presents the results of the calculations of the light curves from the shock breakout epoch to the $^{56}$Co decay. In Section 4, we compare the modeling with observed massive type II SNe. Finally, in Section 5, we provide our summary and discussion.

2. MODELS AND METHODS

2.1. Models

We calculate the light curves of zero-metallicity progenitors using main-sequence masses of $M_{\text{MS}} = 25, 40, 100 M_{\odot}$ and explosion energies corresponding to SNe ($E_{51} = E/10^{51}$ erg = 1) and hypernovae (HNe; $E_{51} > 10$; see Table 1 for details). The presupernova models include detailed postprocess nucleosynthesis calculations (Tomimaga et al. 2007a). Mass loss is considered to be a function of metallicity and is supposed to be zero for Pop III models. The composition of the models after explosive nucleosynthesis and the density structures of presupernova stars are shown in Figure 1. Presupernova stars with $M_{\text{MS}} = 25, 40 M_{\odot}$ are blue supergiants (BSGs), and these progenitor models have been used by Ishigaki et al. (2014) to provide mixing-fallback best-fit models. The transition between red supergiant (RSG) and BSG zero-metallicity stars is still under investigation, and so we add an RSG progenitor model with $M_{\text{MS}} = 100 M_{\odot}$ to provide a more complete picture. The fits of the initial mass distribution to the ensemble of inferred Population III star gives $87^{+11}_{-13} M_{\odot}$ for the maximum progenitor mass (Fraser et al. 2015), which is close to our choice of 100 $M_{\odot}$. For the 100 $M_{\odot}$ model, we did not find good mixing-fallback parameters to fit the observed metal-poor stars; nevertheless, the best models have a small mass of $^{56}$Ni: $M(56\text{Ni}) \sim 10^{-7} M_{\odot}$.

Aspherical effects are taken into account in the mixing-fallback model, which uses three parameters: the initial mass cut $M_{\text{cut}}(\text{ini})$, the outer boundary $M_{\text{out}}(\text{out})$, and the ejection factor $f$ (Tomimaga et al. 2007b). The parameters of the mixing-fallback model are chosen around the values which provide the best fit to the observed elemental abundances (Ishigaki et al. 2014). However, in order to investigate the dependence of the light curves on the ejected mass of $^{56}$Ni, we vary the ejection factor from ordinary supernova values 0.07–0.2 $M_{\odot}$ down to the EMP case of $M(56\text{Ni}) = 10^{-7} M_{\odot}$.

For the 40 and 100 $M_{\odot}$ SN models, we have to slightly increase the explosion energy from $E_{51} = 1$ to 1.3 and to 2, respectively (see Table 1), in order to avoid the numerical oscillation of the internal zones due to fallback in the

### Table 1: Zero Metallicity Explosion Models

| Model | Z | $M$ $(M_{\odot})$ | $T$ $(10^3$ K) | Luminosity $(10^{44} L_{\odot})$ | Radius $(R_{\odot})$ | $M(\text{H})$ $(M_{\odot})$ | Energy $(E_{51})$ | $M_{\text{cut}}(\text{ini})$ $(M_{\odot})$ | $M_{\text{out}}(\text{out})$ $(M_{\odot})$ | $M(56\text{Ni})$ $(M_{\odot})$ | [C/Fe]$^a$ |
|-------|---|------------------|----------------|-------------------------------|------------------|-----------------|-----------------|-----------------|----------------|-----------------|------------------|
| 25/0E1 | 0 | 25               | 40             | 0.32                          | 30               | 11.1            | 1               | 1.7             | 0.2            | 1.6             | 0.9              |
| 25/0E1m | 0 | 25               | 10             | 5.7                           | 1.6             | 0.7             | 0               | 0              | 0.7            | 0.3             |
| 25/0E10 | 0 | 25               | 1.7            | 6.4                           | 0.0             | 6.4             | 0               | 0              | 0.5            | 0.3             |
| 40/0E1.3m | 0 | 40               | 27             | 0.88                          | 85               | 15.0            | 1.3             | 0.2             | 0.6            | 0.6             |
| 40/0E30 | 30 | 0               | 1.7            | 6.4                           | 0.0             | 6.4             | 0               | 0              | 0.5            | 0.3             |
| 100/0E2m | 0 | 100              | 3.5            | 2.2                           | 2200             | 27.1            | 2.0             | 0.0             | 0.6            | 0.6             |
| 100/0E60 | 60 | 0               | 5.5            | 0.3                           | 0.0             | 0.3             | 0.0             | 0              | 0.6            | 0.6             |

Notes. The numbers shown are the metallicity, main-sequence mass, color temperature, luminosity, radius, hydrogen mass, explosion energy, mixing-fallback inner and outer masses, $^{56}$Ni mass, and carbon-to-iron ratio.

$^a$ For mixing-fallback models, the value for the models with the highest amount of $^{56}$Ni is shown.
spherically symmetric approximation. Thus, the luminosities of these models are higher than those for the originally predicted explosion energy $E_51 = 1$. Estimates for the plateau phase (distinctive flat stretch during the decline) provide an increase of 0.3 mag for the 25 $M_\odot$ model and of 0.7 mag for the 100 $M_\odot$ model. As the nucleosynthetic products are not influenced much by the small change in the explosion energy, these changes do not lead to any inconsistency. This fallback issue should be investigated in the future with the use of multidimensional calculations.

In addition to zero-metallicity progenitors, we adopt progenitors with various metallicities up to solar (see Figure 2 and Table 2). The solar metallicity models are RSGs, so that the density and temperature inside the H-rich envelope are approximately several orders of magnitude lower than those of zero-metallicity models.

The solar metallicity models undergo mass loss (Figure 2), which is most significant for the 40 $M_\odot$ model. We do not apply the mixing-fallback scenario for these models, as we use them only for qualitative comparison with zero-metallicity models. The mass of the mixing zone usually does not produce a significant changes in the light curves. However, in order to investigate the mixing effects, we apply the mixing-fallback model to both the 25 $M_\odot$ zero and solar metallicity progenitors.

Similar to zero-metallicity models, in order to avoid numerical oscillations, we have to slightly change the explosion parameters. We adopt an explosion energy larger than $E_51 = 1$ for the 40 $M_\odot$ solar metallicity supernova model 40z002E2 with a low mass cut.

2.2. STELLA Code

For calculations of the light curves, we use the multigroup radiation hydrodynamics numerical code STELLA (Blinnikov et al. 1998, 2000, 2006), and for hypernova simulations we include special relativistic corrections in the hydro code in the manner of Misner & Sharp (1969). STELLA implicitly solves time-dependent equations for the angular moments of intensity averaged over fixed frequency bands and computes variable Eddington factors that fully take into account the scattering and redshifts for each frequency group in each mass zone. Here, we set 200 frequency groups in the range from $10^{-3}$ Å to $5 \times 10^4$ Å. The explosion is initialized as a thermal bomb just above the mass cut, producing a shock wave that propagates outward. The effect of line opacity is treated as an expansion opacity according to the prescription of Eastman & Pinto (1993; see also Blinnikov et al. 1998). The opacity table includes $1.5 \times 10^5$ spectral lines from Kurucz & Bell (1995) and Verner et al. (1996).

3. RESULTS

The results of the light curves calculations for zero-metallicity models are summarized in Table 3 and for non-zero-metallicity models in Table 4. Below, we discourse in detail the results of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Density and temperature of zero-metallicity presupernovae, as well as their composition after explosive nucleosynthesis. The short dashed and long dashed lines correspond to $M_{\text{cut}}$(ini) and $M_{\text{mix}}$(out) in mixing-fallback models.}
\end{figure}
calculations for zero-metallicity models at every phase: from shock breakout through $^{56}$Co decay. We also highlight the modes which reproduce the C-normal EMP ($\frac{\text{[C/Fe]}}{\text{[Fe]}} \approx +1$), CEMP ($\frac{\text{[C/Fe]}}{\text{[Fe]}} \gtrsim 1$), and HMP ($\frac{\text{[C/Fe]}}{\text{[Fe]}} \gtrsim +3$) stars and conduct a comparison with non-zero-metallicity SNe.

### 3.1. Shock Breakout

In this subsection, we mostly describe the properties of zero-metallicity models at the epoch of shock breakout and the difference between the zero and solar metallicity models. A more detailed investigation of Type II plateau supernova (SN II-P) shock breakout for non-zero-metallicity progenitors has been conducted by Tominaga et al. (2011).

The light curves and spectra at the epoch of shock breakout for zero-metallicity models are presented in Figure 3. The duration of the shock breakout is mostly defined by the radius of the progenitors and varies from $\sim 100 \text{s}$ for BSGs up to $\sim 1000 \text{s}$ for RSGs. The peak frequency of BSG models ($25, 40 M_\odot$) is in X-rays and their shock breakout can be detected, for example, by SWIFT/XRT up to $z \sim 0.1$ for SN models and $z \sim 1$ for HN models.

The shape of the spectrum for the 100 $M_\odot$ hypernova model is different from the others because of several density peaks in the outer layers of the ejecta. These peaks are formed due to inefficient gas acceleration (Tolstov et al. 2013), and for such cases more reliable calculations can be performed only in multi-dimensional consideration of fragmentation in the outer layer.
The shock breakout phase of solar metallicity supernovae has a larger luminosity, but the effective temperature is much lower for the same mass compared to that for zero-metallicity supernovae (see Table 4). The main properties of the shock breakouts depend on the radius, the ejecta mass, the explosion energy, the opacity, and the density structure of the external layers (see, e.g., the analytic estimates of Imshennik & Nadezhin 1988; Matzner & McKee 1999). The dependence of the duration of the shock breakout \( \Delta t_{\text{SBO}} \) and the peak luminosity \( L_{\text{SBO}} \) on the presupernova parameters can be estimated as follows (Matzner & McKee 1999):

\[
\Delta t_{\text{SBO}} = 790 \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.58} \left( \frac{E}{10^{51} \text{ erg}} \right)^{-0.79} \times \left( \frac{\rho_1}{\rho_s} \right)^{-0.28} \left( \frac{M}{10M_\odot} \right)^{0.21} \left( \frac{R}{500R_\odot} \right)^{2.16} \text{ s (RSG)},
\]

\[
\Delta t_{\text{SBO}} = 40 \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.45} \left( \frac{E}{10^{51} \text{ erg}} \right)^{-0.72} \times \left( \frac{\rho_1}{\rho_s} \right)^{-0.18} \left( \frac{M}{10M_\odot} \right)^{0.27} \left( \frac{R}{500R_\odot} \right)^{1.90} \text{ s (BSG)},
\]

where \( \kappa, E, M, \) and \( R \) are the opacity, the explosion energy, the mass of the ejecta, and the radius of the presupernova, respectively. The density factor is \( \rho_1/\rho_s \approx 1 \) for RSG models. For BSGs, \( \rho_1/\rho_s \) depends on the density structure, composition, and luminosity of the outer layers of the star and varies from \( \rho_1/\rho_s \approx 50 \) for the \( 25 M_\odot \) model to \( \rho_1/\rho_s \approx 2 \) for the \( 40 M_\odot \) model.

\[
L_{\text{SBO}} = 2.2 \cdot 10^{45} \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.29} \left( \frac{E}{10^{51} \text{ erg}} \right)^{1.35} \times \left( \frac{\rho_1}{\rho_s} \right)^{-0.37} \left( \frac{M}{10M_\odot} \right)^{0.65} \left( \frac{R}{500R_\odot} \right)^{-0.42} \text{ erg s}^{-1} \text{ (RSG)},
\]

\[
L_{\text{SBO}} = 1.9 \cdot 10^{45} \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.39} \times \left( \frac{E}{10^{51} \text{ erg}} \right)^{1.30} \left( \frac{\rho_1}{\rho_s} \right)^{-0.23} \left( \frac{M}{10M_\odot} \right)^{-0.69} \left( \frac{R}{500R_\odot} \right)^{-0.22} \text{ erg s}^{-1} \text{ (BSG)},
\]

Note. The numbers shown are the duration of the light-curve plateau, the luminosity at the midpoint of the plateau, the photosphere velocity at the mid-plateau epoch, the peak luminosity at shock breakout epoch, photosphere velocity at shock breakout epoch, and the number of UV photons in models with \( ^{56}\text{Ni} \) (in brackets are the number of UV photons in the models with \( M(^{56}\text{Ni}) = 0 \)). Plateau characteristics \((\Delta t, \, L, \, u_{\text{ph}})\) are shown for models with \( M(^{56}\text{Ni}) = 0 \).

### Table 3
Zero Metallicity Supernovae Properties

| Model          | \( \Delta t \) (days) | \( L \) \((10^3 L_\odot)\) | \( u_{\text{ph}} \) \((10^6 \text{ km s}^{-1})\) | \( L_{\text{SBO}} \) \((10^3 L_\odot)\) | \( T_{\text{SBO}} \) \((10^8 \text{ K})\) | \( u_{\text{ph,SBO}} \) \((10^6 \text{ km s}^{-1})\) | log\((N_{\text{UV}})\) | \( >13.6 \text{ eV} \) |
|----------------|-----------------------|---------------------------|------------------------|-----------------------------|------------------|-----------------------------|------------------|------------------|
| 25H0E1         | 50                    | 0.06                      | 1.5                    | 6                           | 0.3              | 17                          | 57 (57)          |
| 25H0E1M        | 50                    | 0.06                      | 1.5                    | 8                           | 0.3              | 17                          | 57 (57)          |
| 25H0E10        | 40                    | 0.3                       | 5                      | 50                          | 0.5              | 43                          | 57 (58)          |
| 25H0E10m       | 35                    | 0.4                       | 5                      | 50                          | 0.5              | 43                          | 57 (57)          |
| 40H0E1.3m      | 50                    | 0.1                       | 3                      | 20                          | 0.2              | 15                          | 57 (57)          |
| 40H0E30        | 35                    | 0.9                       | 7                      | 300                         | 0.4              | 53                          | 59 (58)          |
| 40H0E30m       | 30                    | 1.0                       | 7                      | 300                         | 0.4              | 53                          | 59 (58)          |
| 40H0E30m2      | 30                    | 1.2                       | 8                      | 300                         | 0.4              | 53                          | 59 (58)          |
| 100z0E2m       | 135                   | 1.5                       | 3                      | 30                           | 0.05             | 3                           | 59 (59)          |
| 100z0E60       | 70                    | 23.3                      | 16                     | 300                         | 0.1              | 19                          | 60 (60)          |
| 100z0E60m      | 70                    | 34.8                      | 22                     | 300                         | 0.1              | 19                          | 60 (60)          |

### Table 4
Non-zero Metallicity Supernovae Properties

| Model          | \( \Delta t \) (days) | \( L \) \((10^3 L_\odot)\) | \( u_{\text{ph}} \) \((10^6 \text{ km s}^{-1})\) | \( L_{\text{SBO}} \) \((10^3 L_\odot)\) | \( T_{\text{SBO}} \) \((10^8 \text{ K})\) | \( u_{\text{ph,SBO}} \) \((10^6 \text{ km s}^{-1})\) | log\((N_{\text{UV}})\) | \( >13.6 \text{ eV} \) |
|----------------|-----------------------|---------------------------|------------------------|-----------------------------|------------------|-----------------------------|------------------|------------------|
| 20H-3E1        | 105                   | 0.47                      | 4                      | 15                          | 0.07             | 5                           | 58 (58)          |
| 20H002E1       | 115                   | 0.47                      | 4                      | 17                          | 0.07             | 5                           | 58 (58)          |
| 25H002E1       | 125                   | 0.62                      | 3.5                    | 35                          | 0.07             | 4                           | 59 (59)          |
| 25H002E1M      | 135                   | 0.74                      | 4                      | 40                           | 0.07             | 4                           | 59 (59)          |
| 40H002E1       | 80                    | 0.8                       | 4.5                    | 35                          | 0.06             | 3                           | 59 (59)          |
| 40H002E2       | 70                    | 1.7                       | 9                      | 100                         | 0.08             | 4                           | 59 (59)          |
The difference between the RSG and BSG models can clearly be seen from the duration of the peak: the larger presupernova radius leads to a longer duration of the shock breakout epoch. Compared with zero-metallicity BSGs, the larger luminosity of the solar metallicity SNe is due to the lower (by several orders of magnitude) opacity of the external layers of RSGs. The photosphere’s temperature in RSG models is only 3000–4000 K (in contrast to ∼20,000 K in BSG models), and the opacity of neutral atoms of hydrogen is dominated by bound-bound and bound-free transitions. In agreement with theoretical estimates, this low opacity of the external layers increases the luminosity of the shock breakout.

3.2. Cooling Phase and Rising Time

The shock breakout is followed by the “cooling envelope phase,” which marks the decline of the luminosity (see Figure 4). The duration of this phase strongly depends on the presupernova radius. For compact BSG progenitors, the duration is much shorter in the optical U and V bands (∼100 s) than for RSGs (∼1 day). After reaching the luminosity minimum, the light curve starts to rise as the heated expanding stellar envelope diffuses outward. For RSG progenitors, the rise time (∼10 days) an order of magnitude longer than for BSG progenitors. This behavior is consistent with the previous investigation of the SN light curves for the early phases (see, e.g., González-Gaitán et al. 2015).

3.3. Plateau Phase

The presence of the massive hydrogen envelope in zero metallicity presupernova models should produce light curves similar to those of SNe II-P. The duration of the plateau is determined primarily by the mass of the envelope $M_{\text{ej}}$ and the other main outburst properties, i.e., the explosion energy $E$ and the initial radius $R$ (Litvinova & Nadezhin 1985; Popov 1993). The SN II-P light curve tails are believed to be powered by $^{56}$Co decay and the temporal behavior is determined by the ejected mass of $^{56}$Ni (see, e.g., Nadyozhin 1994). The variation of the ejected mass of $^{56}$Ni allows us to cover the uncertainty of matter mixing and fallback in aspherical, jet-like explosions. We start with $M(^{56}\text{Ni}) \sim 0.1\ M_\odot$ and logarithmically decrease down to $10^{-6}\ M_\odot$ by a factor of 10 $M_\odot$. Lower values of $M(^{56}\text{Ni})$ lead to extremely small changes in the light curve ($M_{\text{abs}} < -5$), and for practical purposes the light curve with $M(^{56}\text{Ni}) = 10^{-6}\ M_\odot$ can be used. The light curves for zero-metallicity models are compared with several RSG models with no $^{56}$Ni.

3.3.1. Plateau Luminosity

During the plateau, the light curve is powered by the recombination of hydrogen previously ionized in the supernova...
The peak luminosity increases with higher explosion energy and radius, but decreases with higher ejecta mass. The absolute $V$ magnitude can be estimated from Litvinova & Nadezhin (1985):

$$V = -2.34 \log E - 1.80 \log R + 1.22 \log M - 11.307,$$  \hfill (3)

where $E$, $R$, and $M$ are the explosion energy (in $10^{50}$ erg), the presupernova radius, and the ejecta mass in solar units, respectively.

The calculations of the zero-metallicity models presented in Figure 5 are consistent with the analytic estimates. The plateau of the 25$M_\odot$ and 40$M_\odot$ supernovae that have a compact progenitor is rather faint, $M_{\text{bol}} \sim -15$, while the much larger radius of the 100$M_\odot$ progenitor leads to an increase in luminosity. In contrast to the zero-metallicity 25–40$M_\odot$ models, solar metallicity SNe are about an order of magnitude more luminous (Figure 6) due to the larger radius of their progenitors.

All of the above are valid for models with a low amount of $^{56}$Ni. If the $^{56}$Ni mass in the ejecta is rather high ($M(^{56}\text{Ni}) > 0.01 \ldots 1M_\odot$), then the $^{56}$Ni decay can form a more luminous peak. From Figure 5, we see that the $^{56}$Ni peak is a possible indicator of C-normal EMP stars.

The optical multicolor light curves (Figures 7–8) during the plateau phase demonstrate that the flat shape of the U- and B-band light curves is similar to the shape of the bolometric light

Figure 5. Bolometric light curves of zero-metallicity SNe parametrized by $\log(M(^{56}\text{Ni})/\varepsilon M_\odot)$ for mixing-fallback models (solid line), original non-mixed models (dotted line), and the large mass cut 40Z0E30M2 model (dashed line). Solid lines denote the models with the best fit to metal-poor stars. Colors denote the EMP (turquoise color), CEMP (orange color), and HMP models (red color).

Figure 6. Bolometric light curves for non-zero-metallicity (close to solar metallicity) progenitor models with no $^{56}$Ni (solid line) and the original non-mixed model (dotted line). Dashed line represents model 40Z002E2. In contrast to model 40Z002E1, 40Z002E2 has higher explosion energy $E_{51} = 2$, lower mass cut $M_{\text{cut}} = 1.5M_\odot$, and non-zero nickel mass $M(^{56}\text{Ni}) = 0.7M_\odot$.
Figure 7. Bolometric and UBVRI light curves for zero-metallicity mixing-fallback supernova models (the explosion energy $E_{51} \sim 1$). Solid line—$M(^{56}\text{Ni}) = 0$ (HMP), dashed line—$M(^{56}\text{Ni}) = 10^{-3} M_\odot$ (CEMP), and dotted line—$M(^{56}\text{Ni}) = 10^{-1} M_\odot$ (C-normal EMP).

Figure 8. Bolometric and UBVRI light curves for zero-metallicity mixing-fallback hypernova models (the explosion energy $E_{51} \gtrsim 10$). Solid line—$M(^{56}\text{Ni}) = 0$ (HMP), dashed line—$M(^{56}\text{Ni}) = 10^{-3} M_\odot$ (CEMP), and dotted line—$M(^{56}\text{Ni}) = 10^{-1} M_\odot$ (C-normal EMP).
curve. The shape of the light curves in the more luminous R and I bands is not as flat and has a peak in the middle of the plateau.

3.3.2. Plateau Duration

The duration $\Delta t$ of the light-curve plateau is estimated by Litvinova & Nadezhin (1985) as

$$\Delta t = -0.191 \log E + 0.186 \log R + 0.566 \log M + 1.047.$$  (4)

In agreement with this equation, the larger radius and mass provide a longer duration for the plateau phase, but a larger explosion energy reduces the plateau duration. This behavior is well reproduced in our numerical calculations: in bolometric light curves of zero-metallicity (Figure 5), solar metallicity (Figure 6) models, and in multicolour light curves of zero-metallicity supernova and hypernova models (Figures 7–8).

The width of the plateau also depends on the depth of the mixed hydrogen-rich layer (see, e.g., Shigeyama & Nomoto 1990). To estimate the influence of mixing, we constructed the models with a uniform abundances distribution and performed a comparison with non-mixed models (Figure 9). The mixing does not greatly change the form of the light curve because the minimum velocity of the hydrogen layer is low for the models.

The solar metallicity RSG progenitor has a larger radius which leads to a higher luminosity and a longer duration of the SN plateau compared with BSG progenitors. The $20 M_\odot$ and $25 M_\odot$ RSG models have quite a large amount of $^{56}$Ni to make the plateau duration longer compared with the low-$^{56}$Ni models (Figure 6).

3.3.3. Photospheric Velocities

In Figure 10, we compare the photospheric velocities for $25 M_\odot$ zero and solar metallicity models during the plateau phase. Due to compact presupernova, the zero-metallicity models have a higher velocity and a much faster drop in photospheric velocity. For hypernova models (explosion energy $E_{51} = 10$), the velocity of the outer layers of the ejecta reaches $\sim 50,000$ km s$^{-1}$. The maximum photospheric velocity is realized at the beginning of the plateau phase just after shock breakout epoch.
3.3.4. Color Evolution Curves

Figure 11 presents $B - V$ color evolution curves of $25 M_\odot$ progenitors for various values of explosion energy and metallicity. The color evolution curves reveal a common feature: for zero and low-metallicity BSG progenitors, the $B - V$ value during the plateau phase is almost constant, while for solar metallicity RSG progenitors we can see a gradual reddening.

For a more general investigation, in Figure 11, we compare the color evolution curves calculated with STELLA with a set of SN II-P and SN 1987A observational data. The modeling of the color evolution curves during the plateau phase demonstrates a cooling rate consistent with that observed for SNe: the decrease in metallicity leads to flattening of the color evolution curve. The flattening of the color curve can also be seen in observations of low-metallicity supernovae (see, e.g., Polshaw et al. 2015).

It is difficult to use the luminosity and the duration of the plateau phase to distinguish between solar and low-metallicity SNe (Figure 12). Zero metallicity normal energy SNe are as luminous as solar metallicity low-energy SNe. Moreover, the light curve of the massive $100 M_\odot$ zero-metallicity SNe is quite similar (in the plateau duration and luminosity) to the light curve of less massive ($25 M_\odot$) solar metallicity stars for the same explosion energy $E_{51} = 1$. The decline of the luminosity after the plateau phase is also quite similar between the zero and solar metallicity progenitors (Figure 12). In this situation, the SN color evolution curve can help to distinguish the metallicity of the progenitor.

In Figure 13, we compare the color evolution curves for zero and solar metallicity RSG models and find that they also differ in their cooling rates and, consequently, can be distinguished by metallicity. For the massive zero-metallicity BSG presupernova model (40Z0E1.3), in contrast to RSGs, the plateau is shorter, but again low metallicity leads to the flattening of the color evolution curve.

In addition, we confirm the above metallicity dependence for $100 M_\odot$ models in which the metallicity of the hydrogen envelope changes gradually from zero to the solar value. The result of this numerical experiment is the same as above: for the zero-metallicity model, the $B - V$ and $U - B$ color evolution curves are flat, but the increase in metallicity to the solar value leads to the linear behavior. The color evolution is mostly due to the opacity difference between the zero and solar metallicity models, while the hydrodynamical evolution for both models is similar. In distinguishing between the zero and solar metallicity models, the evolution of the red and infrared color indexes is less informative compared to the $B - V$ color index.

The different behaviors of the low-metallicity and solar metallicity color evolution curves can be used to distinguish between low-metallicity and normal metallicity SNe.

3.4. Transition from Plateau to $^{56}$Co Decay

After the plateau phase for low $^{56}$Ni models, the luminosity starts to decline. The decline rate is defined by the explosion energy (Arnett 1980), opacity, and $^{56}$Ni and H mixing (see, e.g., Kasen & Woosley 2009; Bersten et al. 2011; Nakar et al. 2015).

The $UBVRI$ light curves for low $^{56}$Ni models are summarized in Figures 7–8. The radii of BSGs are smaller compared to those of RSGs and the temperature drops faster (Grasberg et al. 1971; Arnett 1980). This leads to the steeper luminosity decline in optical bands for BSG models.

The presence of $^{56}$Ni finally leads to the tail of the light curve powered by the $^{56}$Co decay and its temporal behavior is given
by (see, e.g., Nadyozhin 1994)

\[ M_{\text{bol}} = -19.19 - 2.5 \log \left( \frac{M_{\text{Ni}}}{M} \right) - 1.09 \frac{t}{\tau_{\text{Ni}}} , \]

(5)

where \( t \) is measured from the moment of explosion \((t = 0)\), \( M_{\text{Ni}0} \) is the total mass of \(^{56}\text{Ni}\) at \( t = 0 \), which decays with a half-life of 6.1 days into \(^{56}\text{Co}\), and \( \tau_{\text{Ni}} = 111.3 \) days.

The smooth radioactive tail is reproduced in all of our numerical calculations with good accuracy.

If we increase the \(^{56}\text{Ni}\) mass from zero in the model, then the radioactive tail becomes more luminous and at some \( t \), the \(^{56}\text{Ni}\) tail up to \( \sim 150 \) days. This behavior is explained by the trapping of thermal photons in the model with \(^{56}\text{Ni}\) where the transparency is lower (due to a larger amount of \(^{56}\text{Fe}\) produced by \(^{56}\text{Ni}\) and \(^{56}\text{Co}\) decay). It takes place until the epoch when radioactive decay overwhelms the emission of thermal photons from the entropy reservoir of the shock heated ejecta of zero \(^{56}\text{Ni}\) model at \( t > 150 \) days. Although further, more detailed study may clarify more fully the nature of this effect, it is not important for the goals of our investigation. The behavior of the light curves in those epochs does not change our conclusions.

### 3.4.1. Mixing

The above estimates for the transition phase do not take mixing into consideration, but accounting for mixing can significantly change the light curve.

To investigate the mixing effect more accurately, we compare a number of 25 \( M_\odot \) models with zero and solar metallicity, varying \( M^{^{56}\text{Ni}} \), and calculating the light curves for all of these models with uniform mixing throughout the ejecta (Figure 14). If \( M^{^{56}\text{Ni}} \) is rather large \((\gtrsim 0.1 \ M_\odot)\), then the mixing reduces the rise time to the \(^{56}\text{Ni}\) peak (model 25z0E1m). For more plateau luminous models, the mixing slightly reduces the plateau duration for the same reason: the \(^{56}\text{Ni}\) peak is shifted to earlier times (model 25z002E1m).

### 3.5. Comparison with Previous Calculations

We compare the simulation of the multiband light curves of the 25 \( M_\odot \) hypernova models \((E_{51} = 10)\) with light curves calculated by Smidt et al. (2014) for similar models. The luminosity of the plateau and its duration are in good agreement with their calculations. The decline of the light curves after the plateau phase is more sloping in STELLA calculations, which is due to different procedures used for the opacity calculations. The luminosity at the tail phase must be specified in the future with more detailed opacity calculations that include millions of lines, similar to the existing procedures for type Ia SNe (private communication with E. Sorokina).

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**Figure 14.** Bolometric light curves for zero and solar metallicity mixing-fallback 25 \( M_\odot \) supernova models (the explosion energy \( E_{51} = 1 \)). Blue and magenta denote the models with uniform mixing throughout the ejecta. Solid line—\( M^{^{56}\text{Ni}} = 0 \) (HMP), dashed line—\( M^{^{56}\text{Ni}} = 10^{-3} M_\odot \) (CEMP), and dotted line—\( M^{^{56}\text{Ni}} = 10^{-4} M_\odot \) (EMP). The green dots denote the bolometric light curve of SN 1987A with \( M^{^{56}\text{Ni}} = 0.07 M_\odot \) (Suntzeff & Bouchet 1990).

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**Detailed opacity calculations and analysis of the transition phase (from the plateau to \(^{56}\text{Co}\) decay) in models with \( M^{^{56}\text{Ni}} \) can help to reveal the physical properties of the presupernova: explosion energy, mixing, and opacity.**

### 4. OBSERVATIONAL PROPERTIES OF POP III AND METAL-POOR CORE-COLLAPSE SUPERNOVAE

#### 4.1. Comparison with the Nearby Supernovae

In Figure 15, the calculated low-\(^{56}\text{Ni}\) light curves are qualitatively compared with several observed massive Type II SNe (SN 1999em, Elmhamdi et al. 2003; SN 1999br, Pastorello et al. 2004; SN 1997D, Benetti et al. 2001; SN 2004fx, Hamuy et al. 2006; SN 1992ba, SN 2006Y Anderson et al. 2014).

The luminosity of the plateau for the observed faint supernova SN 1997D is close to the modeled light curves of SNe that have BSG progenitors. Adjusted for the uncertainty of the observed plateau duration and possible asymmetry features, our BSG models with low metallicity could be good candidates for simulations of these objects, in addition to those simulations which already exist (Turatto et al. 1998; Chugai & Utrobin 2000).

The \( B - V \) color evolution curves of SN 1999em and SN 1999br are included in the set of SN II-P data (Hamuy 2001) presented in Figure 11. Their color curves are typical of solar metallicity progenitors and the presupernovae of SN 1999em and SN 1999br are supposed to have RSG progenitors. The \( B - V \) color evolution curve for SN 1992ba and SN 2004fx are also typical of solar metallicity SNe (Hamuy et al. 2006; Jones et al. 2009).

Since we do not know the moment of explosion in observed SN II-P, it is difficult to distinguish between the low-energy explosion of RSGs \((E_{51} \sim 0.1)\) and the ordinary BSG SN in the analysis of bolometric light curves (see Figure 12). Analysis of the
photospheric velocities and color curve evolution during the plateau phase can provide more information about the progenitor.

4.2. Detectability of Pop III Supernovae

While Pop III SNe typically have fainter and shorter plateaus than SNe with solar metallicity, the most important characteristic is the color evolution curve. The color evolution during the plateau phase and the first 10 days distinguishes Pop III SNe from RSG SNe with solar metallicity and SN 1987A-like BSG SNe, respectively (Figure 13). In order to obtain the color evolution, the multicolor observations should be performed every ~2 days for the first 10 days and every ~10 days for the plateau.

Although follow-up observations of nearby SNe realize such multicolor observations with cadences of <10 days, SNe with flat color evolution have not yet been discovered (Section 4.1). This might be because most previous SN surveys targeted large nearby galaxies with metal enrichment. Untargeted multicolor SN surveys were performed by SDSS (Sako et al. 2014) and SNLS (Astier et al. 2006; Guy et al. 2010). Their cadences are high enough to draw the color evolution curves at the plateau. We have checked the multicolor light curves of the SDSS sample.\footnote{http://data.sdss3.org/sas/dr10/boss/papers/supernova/} Although the signal-to-noise ratio is poor, a spectroscopically identified SN II (ID 12991) shows blue color and flat color evolution curves during the plateau phase (Figure 16). Although the metallicity of the host galaxy is not metal-poor according to the $R_{\alpha}$ method (12+log(O/H) = 8.58, Tremonti et al. 2004; Alam et al. 2015), we propose that the SN took place in the low-metallicity environment. We do not consider red and infrared color evolution curves because it is not informative to distinguish between zero and solar metallicity (see Section 3.3.4).

There are two ways to detect Pop III SNe in low-metallicity environments that produce C-normal EMP, CEMP, and HMP stars. In order to identify low-$^{56}$Ni SNe, we must follow the light curve until $^{56}$Co decay. As the tail of the faint SNe for HMP stars are as faint as $M_{\text{bol}} > -7$, the tail can be detected only if it took place at $< 50$ Mpc even with 8 m class telescopes. In contrast, their plateaus are as bright as $m_{\text{bol}} \sim 20$, and thus the detection can be made with an untargeted survey with such 1 m class telescopes as PTF (Rau et al. 2009), KISS (Morokuma et al. 2014), and the all-sky survey as Gaia with the broadband G-band limiting magnitude of $G \sim 19$ (Altavilla et al. 2012). In Figure 17, we plot light curves for low-$^{56}$Ni models and designate the detection limits for the Gaia mission. For these surveys, EMP...
star forming galaxies can also be good targets for finding and identifying supernovae of metal-poor progenitor stars (Thuan 2008; Pilyugin et al. 2014; Gusev et al. 2015).

The other targets for detecting Pop III SNe are the metal-free pockets at $z \sim 2$. Figure 18 shows the g-band light curves of Pop III SNe at $z = 2$. Since Pop III SNe are fainter than SNe with solar metallicity, only SNe with 100 $M_\odot$ can be observed with 8 m class telescopes such as Subaru/HSC and LSST. Explosions with $E_{51} = 1$ and 60 can be detected during the shock breakout phase and the phase lasting from the shock breakout to the plateau, respectively. The UV colors of Pop III SNe also display flat color evolution, in contrast to the increasing UV color evolution of solar metallicity SNe (Figure 19). Therefore, the multicolor optical observation can inform the metallicity of the SN, although spectroscopic follow-up observation is difficult.

4.3. Contribution to the Ionization

Sources of UV radiation capable of reionizing the universe are still under discussion. According to cosmological models (Barkana & Loeb 2001) and observations (Fan et al. 2006), the reionization of the universe appears to have been well completed at redshift $z \sim 6$. The first generation of stars could be important contributors to the ionization. According to our calculations, the SNe of RSG progenitors provide larger amounts of UV photons at the shock breakout epoch, but still less than BSGs do during their lifetimes.

To estimate the contribution of Pop III SNe to cosmic reionization, we calculate the number of ionizing photons with energy $E_{ion} = h\nu_{HI} > 13.6$ eV for all of the models:

$$N_{UV} = \int_{\nu_{HI}}^{\infty} \frac{E}{h\nu} d\nu.$$  

(6)

The results are summarized in the last column of Table 3. The UV photons are mostly produced by shock breakout when the effective temperature is high enough ($T \sim 5 \times 10^5$ K), similar to previous estimates from the SN 1987A model (Lundqvist & Fransson 1996). Supernovae with larger explosion energies or larger progenitor radii emit larger numbers of UV photons. However, for BSG progenitors, the number of UV photons during explosions corresponds to only 10–100 years of the main-sequence lifetime (Tumlinson & Shull 2000). RSG progenitors provide a larger amount of UV photons at shock breakout, but still less than those from BSGs during their lifetimes.

5. CONCLUSIONS

We have calculated the light curves for a number of hydrodynamical models for Pop III 25–100 $M_\odot$ core-collapse SNe ($E_{51} \sim 1$) and HNe ($E_{51} \sim 10$). These models are assumed to undergo mixing and fallback to produce nucleosynthesis yields which are well fit to the observed abundance patterns of EMP, HMP, and CEMP stars.

The radiation-hydrodynamical simulations reproduce in detail the shock breakout, plateau phase, and radioactive tail of the light curves. The observations of the shock breakout and the multicolor light curves of the plateau phase are important for the identification of zero- and low-metallicity SNe.

BSGs are typical presupernova for Pop III core-collapse SNe with $M \lesssim 40–60 M_\odot$ and their structure determines the properties of shock breakout: shorter duration and lower luminosity compared to more massive RSG progenitors. The plateau phase is common to both BSG and RSG models and is important for the identification of zero- and low-metallicity SNe.

The low amount of $^{56}$Ni used to explain CEMP stars with mixing-fallback leads to a sharp luminosity decline after the
plateau phase. This feature also can be used as an indicator of a low-metallicity progenitor. The transition phase from the plateau to the tail can provide us with additional information about the explosion energy, mixing, and opacity of the presupernova, but it requires more accurate theoretical consideration of the opacities in numerical simulations.

We have modeled Pop III SNe with one-dimensional simulations. The aspherical effects are taken into account approximately with the mixing-back model. The mixing of H and $^{56}$Ni could have a large impact on the shape of the light curve and future multi-dimensional radiation calculations are needed to investigate more accurately the effects of asphericity.

The direct detection of Pop III core-collapse SNe is hardly possible at high redshift (Whalen et al. 2013), but Pop III hypernovae will be visible to the James Webb Space Telescope (JWST) at $z \sim 10–15$ (Smidt et al. 2014). The probability of the detection of Pop III SNe in metal-free gas pockets ($z \sim 2$) would be higher because their detection would be possible with current surveys (HSC/Subaru).

Along with Pop III SNe, the results our modeling was suitable for the identification of low-metallicity supernovae in the nearby universe. The BSG progenitors are supposed to have metallicities up to $Z \sim 10^{-5}$–$10^{-4}$. There are a number of galaxies in the local universe with metallicities close to these values (Papaderos et al. 2008; Pilyugin et al. 2014) and, taking into account inhomogeneous galaxy regions, there could be a good chance of identifying and studying these objects. The number of discovered faint supernovae is increasing (Nomoto 2012) and new surveys such as LSST and JWST are planned to make a large contribution to the detection of low-metallicity supernovae.

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