SHOCK BREAKOUT IN TYPE II PLATEAU SUPERNOVAE: PROSPECTS FOR HIGH-REDSHIFT SUPERNOVA SURVEYS

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ABSTRACT

Shock breakout is the brightest radiative phenomenon in a supernova (SN) but is difficult to be observed owing to the short duration and X-ray/ultraviolet (UV)-peaked spectra. After the first observation from the rising phase reported in 2008, its observability at high redshift is attracting enormous attention. We perform multigroup radiation hydrodynamics calculations of explosions for evolutionary presupernova models with various main-sequence masses $M_{\text{MS}}$, metallicities $Z$, and explosion energies $E$. We present multicolor light curves of shock breakouts in Type II plateau SNe, being the most frequent core-collapse SNe, and predict apparent multicolor light curves of shock breakout at various redshifts $z$. We derive the observable SN rate and reachable redshift as functions of filter $x$ and limiting magnitude $m_{\text{lim}}$ by taking into account an initial mass function, cosmic star formation history, intergalactic absorption, and host galaxy extinction. We propose a realistic survey strategy optimized for shock breakout. For example, the $g'$-band observable SN rate for $m_{\text{lim}} = 27.5$ mag is $3.3$ SNe deg$^{-2}$ day$^{-1}$ and half of them are located at $z \gtrsim 1.2$. It is clear that the shock breakout is a beneficial clue for probing high-$z$ core-collapse SNe. We also establish ways to identify shock breakout and constrain SN properties from the observations of shock breakout, brightness, timescale, and color. We emphasize that the multicolor observations in blue optical bands with $\sim$hour intervals, preferably over $\gtrsim 2$ continuous nights, are essential to efficiently detect, identify, and interpret shock breakout.

Key words: radiative transfer – shock waves – stars: evolution – supernovae: general – surveys

Online-only material: color figures

1. INTRODUCTION

In contrast to Type Ib supernovae (SNe), systematic observational studies of core-collapse supernovae (CCSNe) have been restricted at a redshift $z \lesssim 1$ (e.g., Poznanski et al. 2007). This is because CCSNe are typically fainter than Type Ia SNe (e.g., Richardson et al. 2002), except for rare energetic supernovae (hypernovae, e.g., SN 1998bw; Galama et al. 1998) or recently found extremely bright SNe (e.g., Quimby et al. 2009).

Recent improvements of telescopes/instruments and well-organized survey strategies make it possible to detect unusual core-collapse events at high redshift: for example, bright Type IIb SNe (SNe IIb) at $z > 2$ (Cooke et al. 2009) and gamma-ray bursts (GRBs) up to $z \sim 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009). With the use of the high-$z$ accessibility of these events, a star formation history (SFH) and an initial mass function (IMF) at high redshift are intensively studied (e.g., Kistler et al. 2009; Wang & Dai 2009; Cooke et al. 2009). However, special conditions are required to realize such events, i.e., a dense circumstellar matter for an SN IIn (e.g., Chugai et al. 2004) and a fast-rotating progenitor for a GRB (e.g., Woosley 1993). Thus, they cannot be the main constituents of CCSNe, and the SFH and IMF estimated with them could involve large biases. Hence, ways to directly detect normal CCSNe at high redshift are required to investigate the nature of the majority of CCSNe and estimate the SFH and IMF with small biases.

The bolometrically brightest phenomenon in the SN with a shockwave is shock breakout. In a CCSN explosion, an outward shockwave forms around a central remnant by depositing released gravitational energy. The shockwave propagates through a stellar envelope to heat it up and accelerates its expansion. Since the star is optically thick, the shockwave cannot be electromagnetically observed until its emergence from a stellar surface. When the shockwave approaches the stellar surface at a distance with an optical depth $\gtrsim 10$, radiation from the shock front starts to leak out and a hot fire ball suddenly appears to emit a bright soft X-ray and ultraviolet (UV) flash with a quasi-blackbody spectrum ($T > 10^4$ K). This phenomenon is the shock breakout, which has been theoretically predicted by, e.g., Klein & Chevalier (1978). Its duration strongly depends on the presupernova radius. Brightness rises in several seconds to several hours and declines in several ten seconds to several days. Theoretical studies have suggested that the peak bolometric luminosity exceeds $10^{44}$ erg s$^{-1}$ (e.g., Blinnikov et al. 2000) and that shock breakout is observable even if it takes place at $z \gtrsim 1$ (e.g., Chugai et al. 2000). However, the short duration and soft X-ray/UV-peaked spectra had made detection of shock breakout difficult for a long while, except for the fortunate detection of its tail in nearby SNe in the $U$ band (e.g., SN 1987A, Catchpole et al. 1987; SN 1993J, Richmond et al. 1994; SN 1999ex, Stritzinger et al. 2002).

The first detection of shock breakout in the rising phase was obtained serendipitously in 2004–2008 and reported in 2008: Type Ib SN 2008D in NGC 2770 (distance $d = 27$ Mpc;
For SN 2008D, an X-ray light curve (LC) from the breakout and optical LCs after a tail were observed (e.g., Soderberg et al. 2008; Modjaz et al. 2009). The X-ray LC rises in ~60 s and declines in ~130 s but it is not clear whether the X-ray spectral energy distribution (SED) is thermal or nonthermal. For the SNLS SNe II-P, UV LCs of the shock breakout and optical LCs of the plateau were observed (e.g., Schawinski et al. 2008; Gezari et al. 2008). The UV flash of SNLS-04D2dc rises and declines in several hours and the subsequent UV LC shows rebrightening in several days. However, the signal-to-noise ratios of the UV data are too low to obtain the SED.

The observational papers and subsequent papers present theoretical models for shock breakout: analytic models for SN 2008D (e.g., Soderberg et al. 2008; Chevalier & Fransson 2008; Modjaz et al. 2009) and hydrodynamics calculation with two-temperature radiative diffusion (Schawinski et al. 2008) and a one-temperature radiation hydrodynamics calculation coupled with non-local thermodynamic equilibrium (non-LTE) spectral calculation for SNLS-04D2dc (Gezari et al. 2008). Tominaga et al. (2009) have performed a multigroup radiation hydrodynamical calculation for the first time and successfully constructed a self-consistent radiation hydrodynamical model for SNLS-04D2dc. They have presented that an SN explosion of a 20 $M_\odot$ star with an explosion energy $10^{51}$ erg reproduces well the UV–optical LCs of the shock breakout and plateau. Also, the successful model demonstrates that an SN similar to SNLS-04D2dc is detectable at $z = 1$ with 8 m class optical telescopes.

The UV-bright shock breakout is followed by a plateau phase. It appears as an SN II-P that is most frequent among core-collapse SNe (e.g., Mannucci et al. 2008; Arcavi et al. 2010; Li et al. 2011; Smith et al. 2011). In contrast to an SN IIn and a GRB, the formation of a plateau phase does not require any specified conditions other than the presence of a thick H envelope. Therefore, the SFH estimated with shock breakouts in SNe II-P should have smaller uncertainties and biases than those with SNe IIn or GRBs. Moreover, observational properties of the shock breakout—the brightness, color, and timescale—depend on properties of the SN and its progenitor, the explosion energy $E$, presupernova radius $R_{\text{presN}}$, and ejecta mass $M_{ ej}$ (e.g., Matzner & McKee 1999). Thus, it is possible to derive detailed properties of SN explosions from the observations of shock breakout and constrain an IMF precisely.

Shock breakout is coming under the spotlight to probe high-$z$ CCSNe but the observable properties are poorly understood. Therefore, in order to execute a shock breakout survey effectively, one is required to provide theoretical predictions for observable quantities and propose strategies of observations and analysis to detect, identify, and interpret them. Hence, we perform multigroup radiation hydrodynamics calculations of shock breakouts in SNe II-P with various $M_{ MS}$, $z$, and $E$ with a multigroup radiation hydrodynamics code STELLA (Blinnikov et al. 1998, 2000, 2006) and present theoretical predictions of apparent multicolor LCs at various redshifts. Based on the theoretical models, we estimate the number of detections and reachable redshift, clarify requirements on survey strategies, and develop ways to identify shock breakout and to derive the SN properties from the observational quantities of shock breakout.

In Section 2, the applied models and methods are briefly described. In Section 3, results are shown. We present the multicolor LCs of shock breakouts (Section 3.1) and predictions of apparent multicolor LCs of shock breakouts (Section 3.2). In Section 3.3, we offer future prospects on shock breakout surveys: an expected number of detection and reachable redshift (Section 3.3.1), dependencies on extinction and SFH (Section 3.3.2), requirements on survey strategies (Section 3.3.3), ways to identify shock breakouts (Section 3.3.4), and ways to constrain SN properties (Section 3.3.5). In Section 4, the conclusion and discussion are presented.

2. MODELS AND METHODS

2.1. Progenitor Model and Explosive Nucleosynthesis

We adopt progenitor models with various $M_{ MS}$ (= 13, 15, 18, 20, 25, 30, and 40 $M_\odot$) and $Z$ (= 0.001, 0.004, and 0.02) which are taken from Umeda & Nomoto (2005). The stellar evolution calculations include a mass loss depending on metallicity $Z$, which is assumed to be proportional to $Z^{0.5}$ (Kudritzki 2000). Since shock breakout arises at a thin surface layer with an optical depth $\tau \lesssim 10$, we adopt the stellar surface sufficiently outside which is as shallow as $\tau = 0.001$. The density structures of the progenitor models are shown in Figures 1(a) and 1(b). The properties of progenitor models, $M_{ MS}$, $Z$, presupernova mass $M_{\text{presN}}$, presupernova radius $R_{\text{presN}}$, and presupernova luminosity $L_{\text{presN}}$ are summarized in Table 1.1 The density inversion at the outermost layer corresponds to a super-adiabatic layer, where the temperature gradient is steeper than the adiabatic case.

We calculate explosive nucleosynthesis adopting the same method as described in Tomimaga et al. (2007); the explosion is initiated as a thermal bomb, hydrodynamics is calculated including nuclear energy generation with the $\alpha$-network, and a nucleosynthesis calculation is performed as a postprocessing procedure. Since explosive nucleosynthesis ceases well before the shock emergence from the stellar surface, we perform a radiation hydrodynamics calculation of an explosion for a model with the abundance distribution after explosive nucleosynthesis and the hydrodynamical structure of the progenitor model.

2.2. Radiation Hydrodynamics

We use the multigroup radiation hydrodynamics code STELLA (Blinnikov et al. 1998, 2000, 2006). The details of STELLA are described in archival literatures (Blinnikov et al. 1998, 2000, 2006).
and its reliability has been carefully verified by comparisons with analytic solutions (Matzner & McKee 1999; Rabinak & Waxman 2011), other numerical codes (Blinnikov et al. 1998, 2003), and multicolor SN observations (Blinnikov et al. 1998, 2000, 2006; Chugai et al. 2004). Here, we briefly describe the assumptions and procedures applied in *stella* and the setup adopted in this paper.

*stella* implicitly solves the time-dependent equations for the angular moments of intensity averaged over fixed frequency bands and computes variable Eddington factors that fully take into account scattering and redshifts for each frequency group in each mass zone. The γ-ray transfer is calculated using a one-group approximation for the nonlocal deposition of the energy of radioactive nuclei; we follow Swartz et al. (1995; see also Jeffery 1998) and use a purely absorptive opacity for γ-ray. It is worth noting that the γ-ray transfer does not influence the results in this paper because there is no contribution to shock breakout from the radioactive decays. In the equation of state, LTE ionizations and recombinations are taken into account. 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).

We adopt 100 frequency bins dividing logarithmically from ν = 6 × 10^{13} Hz (λ = 5 × 10^{4} Å) to 3 × 10^{18} Hz (1 Å); such a number of frequency bins are enough to solve non-equilibrium continuum radiation and treat any SEDs accurately. We emphasize that there is no need to ascribe any temperature to the radiation. The coupling of multigroup radiation transfer with hydrodynamics enables us to obtain the color temperature in a self-consistent calculation, i.e., a luminosity-weighted blackbody fitting of the SED.

All previous computations with *stella* employed the assumptions used in the code EDDINGTON (Eastman & Pinto 1993) for bound-free transitions, in which all atoms and ions, except for hydrogen, are in ground states. Since new opacity tables for *stella* will be released including excited levels in bound-free absorption (E. Sorokina 2011, in preparation) and inner-shell photoionization (P. Baklanov 2011, in preparation), we briefly examine these effects on SEDs for a model with M_{MS} = 20 M_{⊙}, Z = 0.02, and explosion energy E_{51} = E/(10^{51} erg) = 1. While the inner-shell photoionization cross-sections are based

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**Table 1**

| M_{MS} (M_{⊙}) | Z   | M_{preSN} (M_{⊙}) | R_{preSN} (R_{⊙}) | L_{preSN} (10^{45} L_{⊙}) |
|----------------|-----|-------------------|--------------------|--------------------------|
| 13             | 0.02| 12.7              | 564                | 5.57                     |
| 15             | 0.02| 14.1              | 507                | 4.69                     |
| 18             | 0.02| 16.7              | 713                | 8.81                     |
| 20             | 0.02| 18.4              | 795                | 11.1                     |
| 25             | 0.02| 21.7              | 1200               | 23.9                     |
| 30             | 0.02| 25.0              | 1360               | 31.4                     |
| 40             | 0.02| 21.7              | 1660               | 53.8                     |
| 20             | 0.001| 19.7              | 756                | 18.6                     |
| 20             | 0.004| 19.7              | 756                | 13.4                     |
| 20             | 0.05 | 17.3              | 1050               | 15.7                     |
on formulae derived by Verner et al. (1993, 1996a) and Verner & Yakovlev (1995) as in old eddington and stella routines, the case with excited levels treats all bound-free transitions, also for ground levels, by different fitting formulae as in wmbasic.

The SEDs with three different opacity prescriptions are shown in Figure 2. Although there are small differences (<0.3 mag) in several frequency bins, the differences are diluted and diminished when SEDs are convolved with broadband filters. This illustrates that stella results are robust with respect to different approximations for bound-free transitions at least for shock breakout in an SN II-P in which temperature is not extremely high ($T < 10^6$ K). Therefore, in this paper we adopt a procedure from Eastman & Pinto (1993). The opacity table includes 1.5 $\times$ 10$^5$ spectral lines from Kurucz & Bell (1995) and Verner et al. (1996b).

3. RESULTS

3.1. Synthetic Multigroup Light Curves

We perform the multigroup radiation hydrodynamics calculations for models with various $M_{\text{MS}}, E,$ and $Z$. Here, for simplicity, we set $M_{\text{ej}}$ to yield a canonical amount of $^{56}\text{Ni}$ without mixing to the envelope (the ejected $^{56}\text{Ni}$ mass $M(^{56}\text{Ni}) = 0.07 M_\odot$). We note that the assumption does not affect the results because the radioactive decays do not contribute to shock breakout. In this paper, we adopt the AB magnitude system and the followings are small. The SEDs and color temperature evolution depend on $M_{\text{MS}}$ and $Z$ respectively. The models with larger $M_{\text{MS}}$ and higher $Z$ have larger $R_{\text{preSN}}$, except for the model with $M_{\text{MS}} = 15 M_\odot$, and thus have a broader and slightly fainter peak. On the other hand, the models with higher $E$ have a brighter and narrower peak. While the bolometric luminosities decline monotonically with time due to an adiabatic cooling, there could be rebrightening in homochromatic LCs due to the shift of peak wavelength with time.

The SEDs at the bolometric peak ($t = 0$) are shown in Figures 4(a)–(c). The bolometric peak of each model is shown in Figures 5(a)–(c). The color temperatures range from $\lambda \gtrsim 400$ Å, while the luminosities at $\lambda \gtrsim 400$ Å are higher for larger $R_{\text{preSN}}$ and slightly higher for higher $E$. Evolution of color temperature is shown in Figures 5(a)–(c). The color temperatures range from $T_c \sim 2 \times 10^5$ to $T_c \sim 5 \times 10^5$ K at $t = 0$ depending on $M_{\text{MS}}$ and $E$. The SEDs and color temperature evolution depend on $M_{\text{MS}}$ (i.e., $R_{\text{preSN}}$) and $E$, while their dependencies on $Z$ are small.

The light-travel time effect in an aspherical explosion is investigated in, e.g., Couch et al. (2009) and Suzuki & Shigeyama (2010).
The semi-analytical solutions for shock breakout by Matzner & McKee (1999) provide radiation temperature $T_{\text{MM99}}$, outburst energy $E_{\text{MM99}}$, timescale $t_{\text{MM99}}$, and luminosity $L_{\text{MM99}}$ for polytropic envelope structures; the light-travel time or limb darkening corrections are not included. In order to compare our results with the semi-analytical solutions, 

\[ \frac{E_{\text{MM99}}}{t_{\text{MM99}}} \]
we extract the four following characteristics of shock breakout from the corrected and uncorrected models: \( T_{\text{c, peak}} \), color temperature at \( t = 0 \); \( t_{\text{1 mag}} \), days until bolometric magnitude declines by 1 mag after the bolometric peak; \( E_{\text{rad,1 mag}} \), radiation energy emitted from \( t = -t_{\text{1 mag}} \) to \( t = t_{\text{1 mag}} \); and \( L_{\text{peak}} \), peak bolometric luminosity. The properties of our models are summarized in Table 2. Their dependencies on \( R_{\text{preSN}} \) and \( E \) are shown in Figures 6(a)–(h) and compared with the semi-analytical solutions. Since the semi-analytical solutions slightly depend on \( M_{\odot} \), it is different in the numerical models by a factor of \( \sim 2 \). Possible ranges of the semi-analytical solutions are shown in Figures 6(a)–(h).

Comparing the uncorrected models and the semi-analytical solutions, they are quantitatively different but the dependencies are roughly consistent. The models with larger \( R_{\text{preSN}} \) have lower \( T_{\text{c, peak}} \), longer \( t_{\text{1 mag}} \), and higher \( E_{\text{rad,1 mag}} \). The models with higher \( E \) have higher \( T_{\text{c, peak}} \), \( E_{\text{rad,1 mag}} \), and \( L_{\text{peak}} \) and shorter \( t_{\text{1 mag}} \). The models with different \( Z \) are distributed along a sequence of the models with different \( R_{\text{preSN}} \). This indicates that the variations with \( Z \) can be interpreted by the variation with \( R_{\text{preSN}} \) and that the metallicity alters shock breakout mainly through the variation of stellar structure. Accordingly, the \( Z = 0.02 \) models could be applied even for shock breakouts in stars with different \( Z \) if they have the same \( R_{\text{preSN}} \).  

The difference between \( T_{\text{c, peak}} \) and \( T_{\text{MM99}} \) partly stems from the fact that the color temperature is different from the radiation temperature by definition when the opacity depends on frequencies and the SED is not blackbody. However, it is notable that the semi-analytical solution is roughly consistent with the numerical models if \( T_{\text{MM99}} \) is reduced by a factor of 1.5 (Figures 6(a) and (b)). The semi-analytical solutions give slightly higher values also for the other properties. They are in agreement with the numerical models if \( t_{\text{MM99}} \), \( E_{\text{MM99}} \), and \( L_{\text{MM99}} \) are reduced by a factor of 2, 3, and 1.5, respectively (Figures 6(c)–(h)). The reduction factors make it possible to approximately derive progenitor properties from a direct comparison between observations and the semi-analytical solutions. Moreover, the qualitative consistency with the semi-analytical solutions supports the reliability of our numerical results.

The light-travel time and limb darkening corrections slightly reduce \( T_{\text{c, peak}} \) and enhance \( E_{\text{rad,1 mag}} \) but do not change their dependencies. On the other hand, the corrections considerably change the dependencies of \( t_{\text{1 mag}} \) on \( R_{\text{preSN}} \) and \( E \), and the dependence of \( L_{\text{peak}} \) on \( E \). This is because the corrections smear the LC peak and redistribute radiation energy emitted at bright epochs to a time range of \( R_{\text{ph}}/c \), where \( R_{\text{ph}} \) is the photospheric radius. Consequently, the corrections lengthen \( t_{\text{1 mag}} \) and diminish \( L_{\text{peak}} \) more efficiently for a model with shorter \( t_{\text{1 mag}} \) and brighter \( L_{\text{peak}} \). Shock breakout in the model with smaller \( R_{\text{preSN}} \) and higher \( E \) has shorter \( t_{\text{1 mag}} \) and brighter \( L_{\text{peak}} \) (Figures 6(c)–(d) and (g)–(h)) and thus is more strongly corrected.

\[ T_{\text{c, peak}} \times 10^5 \text{K} \]
\[ E_{\text{rad,1 mag}} \times 10^{44} \text{erg} \text{s}^{-1} \]
\[ L_{\text{peak}} \times 10^{44} \text{erg} \text{s}^{-1} \]

\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
\( M_{\odot} \) & \( Z \) & \( E \) & \( M_{\odot} \) & \( T_{\text{c, peak}} \) & \( t_{\text{1 mag}} \) & \( L_{\text{peak}} \) & \( T_{\text{c, peak}} \) & \( t_{\text{1 mag}} \) \\
\hline
13 & 0.02 & 1 & 11.2 & 3.56 & 0.651 & 0.691 & 10.3 & 3.35 \\
15 & 0.02 & 1 & 12.7 & 3.68 & 0.512 & 0.536 & 10.2 & 3.48 \\
18 & 0.02 & 1 & 15.2 & 3.03 & 0.994 & 0.948 & 9.41 & 2.87 \\
20 & 0.02 & 1 & 16.8 & 2.80 & 1.19 & 1.11 & 9.11 & 2.70 \\
25 & 0.02 & 1 & 19.9 & 2.17 & 2.94 & 2.07 & 6.78 & 2.04 \\
30 & 0.02 & 1 & 23.0 & 1.99 & 3.51 & 2.39 & 6.52 & 1.87 \\
40 & 0.02 & 1 & 19.6 & 2.01 & 5.16 & 4.57 & 8.55 & 1.92 \\
40 & 0.02 & 4 & 19.8 & 3.23 & 1.27 & 4.20 & 32.5 & 3.08 \\
40 & 0.02 & 10 & 19.7 & 4.38 & 0.763 & 6.83 & 89.6 & 3.96 \\
20 & 0.001 & 1 & 17.9 & 2.57 & 1.35 & 0.896 & 8.80 & 2.76 \\
20 & 0.004 & 1 & 17.8 & 2.91 & 1.09 & 0.986 & 8.09 & 2.31 \\
20 & 0.05 & 1 & 15.7 & 2.41 & 2.14 & 1.80 & 8.09 & 2.31 \\
\hline
\end{tabular}
Figure 6. Comparisons among the models with corrections (filled circles), the models without corrections (open circles), and semi-analytical solutions (original: cyan shaded region and reduced: gray shaded region). The color of symbols represents $Z = 0.02$ models (red); $M_{\text{MS}} = 20 M_\odot$ models with $Z = 0.001, 0.004,$ and $0.05$ (blue); and $M_{\text{MS}} = 25 M_\odot$ models with $E_{\text{Si}} = 1, 4, 10,$ and $20$ (green). (A color version of this figure is available in the online journal.)

3.2. Shock Breakout at High Redshift

The theoretical multigroup LCs allow us to predict apparent LCs of SNe taking place at arbitrary distance, direction, and host galaxy. Let us consider the case where we observe an object at redshift $z$ that emits light with a luminosity per unit frequency $L_{\nu}$ at frequency $\nu_0$ in the rest frame and we detect the object with a flux per unit frequency $f_{\nu_{\text{obs}}}$ at frequency $\nu_{\text{obs}}$ in the observer frame. Here, $\nu_{\text{obs}} = \nu_0/(1 + z)$. The observed flux is obtained as follows:

$$f_{\nu_{\text{obs}}} = \frac{1}{4\pi D_t^2} (1 + z) L_{\nu_0} (\nu_0),$$

where $D_t$ is the luminosity distance. Here, for cosmological parameters we adopt the five-year results of the Wilkinson Microwave Anisotropy Probe (Komatsu et al. 2009): $H_0 = 70.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $k = 0$, $\Omega_m = 0.726$, and $\delta\Omega_m = 0.274$. Apparent multicolor LCs are derived by convolving the diluted and redshifted multigroup LCs with the bandpasses of the satellites or telescopes.

The LCs in the $g'$ band for $z = 0.2, 0.5, 1, 1.5, 2, 2.5,$ and $3$; LCs in the F322W band for $z = 0.5, 1, 1.5, 2, 2.5,$ and $3$; and LCs in the NUV and $J$ bands for $z = 0.05, 0.1, 0.15, 0.2, 0.25,$ and $0.3$ are shown in Figures 7(a)–(m), 8(a)–(m), 9(a)–(m), and 10(a)–(m), respectively. These figures also show the limiting magnitudes of telescopes/instruments with wide-field imaging capability: $GALEX$ satellite in NUV band for $5 \sigma$ detection with $1500 \text{ s}$ integration ($m_{\text{NUV,lim}} = 22.7 \text{ mag}$; Morrissey et al. 2005, 2007; Figures 9(a)–(m)). Subaru/Suprime-Cam in the $g'$ band for a $5 \sigma$ detection with $1 \text{ hr}$ integration ($m_{\text{g',lim}} = 27.5 \text{ mag}$; Miyazaki et al. 2002; Figures 7(a)–(m)), VLT/HAWK-I in the $J$ band for a $5 \sigma$ detection with $1 \text{ hr}$ integration ($m_{\text{J,lim}} = 24.8 \text{ mag}$; Kessler-Patig et al. 2008; Figures 10(a)–(m)), and the JWST/Near Infrared Camera (NIRCam) in the F322W band for a $10 \sigma$ detection with $10^4 \text{ s}$ integration ($9.18 \text{ nJy}$; Figures 8(a)–(m)). No extinction and no intergalactic medium (IGM) absorption are adopted here.

These figures demonstrate that the shock breakout with higher $E$ or larger $R_{\text{preSN}}$, i.e., larger $M_{\text{MS}}$ or higher $Z$, can be detected at higher redshift. The shock breakout can be detected in the $g'$ band even at $z \sim 1$ (13 and $15 M_\odot$ models), $z \sim 2$ (18 and $20 M_\odot$ models), and $z \sim 3$ (25, 30, and $40 M_\odot$ models). On the other hand, the observations in the NUV and near-infrared (NIR) bands can detect shock breakout only at $z \lesssim 0.5$, although SNe at the later epoch, i.e., plateau stage, are detectable even at $z \gtrsim 4$ by JWST (N. Tominaga et al. 2011, in preparation). This is because the limiting magnitude in UV bands is much shallower than that in optical bands, and the SED of shock breakout is too blue for the NIR observations. The shock breakout has a blue color in optical (Figures 11(a)–(m)), hence an observation in bluer optical bands is more suitable to detect shock breakout as long as the IGM absorption is irrelevant in the adopted bandpass.

Shock breakout has large negative $K$-corrections between the rest-frame $x$ band and the observer-frame $x$ band, $K_x$, where $x$ band is an arbitrary bandpass at $\lambda > 100 \text{ Å}$. Figure 12(a) shows $K_{\text{NUV}}$, $K_{\text{NIR}}$, $K_{\gamma}$, $K_{\gamma'}$, $K_{\gamma''}$, and $K_{\delta}$ of the $20 M_\odot$, $Z = 0.02$, and $E_{\text{Si}} = 1$ model at $t = 0$. Since the SED at $t = 0$ is extremely blue, the negative $K$-corrections are larger for higher redshift even in the FUV band and the $K$-corrections in redder bands are smaller than those in bluer bands. Figure 12(b) shows $K_{\gamma'}$ of the $Z = 0.02$ models with different $M_{\text{MS}}$ at $t = 0$. The more massive models have slightly larger $K$-corrections by $\lesssim 0.5 \text{ mag}$ at $z \lesssim 4.5$. Figure 12(c) shows the evolution of $K_{\gamma'}$ of the $15 M_\odot$ and $30 M_\odot$ models. The $K$-correction evolves more rapidly for higher redshift or smaller $M_{\text{MS}}$. As a result, $K_{\gamma'}$ of the $15 M_\odot$ model is smaller at $t = 0$ but larger at $t_{\text{obs}} = 1.5 \text{ days}$ than that of the $30 M_\odot$ model, where $t_{\text{obs}}$ is a time from $t = 0$ in the observer frame.

Figures 13(a)–(m) show the distance modulus and apparent peak $g'$-band magnitudes $m_{g',\text{peak}}$ of models as a function of redshift for different assumptions on the host galaxy extinction and IGM absorption (Madau 1995). Here, we assume that the host

17 The limiting magnitude is calculated with the Subaru Imaging Exposure Time Calculator (http://www.stsci.edu/jwst/instruments/nircam/sensitivity/index_html) assuming $0.7 \text{ mJ}$. 1.5 aperture, and 3 days from New Moon.

18 http://www.stsci.edu/jwst/instruments/nircam/sensitivity/index_html
in the extinction, while the IGM absorption becomes relevant at the earliest universe (e.g., Hopkins & Beacom 2006), and available optical facilities are numerous compared with X-ray detectors. (2) A multiepoch imaging observation in a night is essential to draw the LCs of shock breakout in both rising and declining phases because the timescale of shock breakout in an SN II-P at z ≳ 2 is long enough to be detected with current optical facilities (Section 3.2). Such a survey is promising because of three reasons: the duration of a distant event is elongated, the star formation rate (SFR) is high in the distant universe (e.g., Hopkins & Beacom 2006), and available optical facilities are numerous compared with X-ray/UV satellites. (2) A multiepoch imaging observation in a night is essential to draw the LCs of shock breakout in both rising and declining phases because the timescale of shock breakout in an SN II-P at z ≳ 2 is less than ~1 day in the observer frame (Section 3.2).

In the following, we estimate the expected number and highest redshift of detection, discuss influences of uncertainties on host galaxy extinction and SFH, and propose realistic and promising survey strategies, ways to identify shock breakout, and ways to constrain the SN properties from observable quantities. In this section, we focus on the models with E51 = 1 and Z = 0.02.

3.3. Future Prospects for Shock Breakout Surveys

The detection of shock breakout has recently been consumed with the number of detections is still small. This is because it is difficult for past/ongoing SN/transient surveys with intervals of several days to detect short-term soft X-ray/UV flashes. Hence, we propose a deep optical survey with short intervals, e.g., ~ hour, for shock breakout in an SN II-P in the distant universe.

This is motivated by the following two brand-new prospects. (1) Due to the large negative K-correction, distant shock breakout up to z ≳ 3 is bright enough to be detected with current optical facilities (Section 3.2). Such a survey is promising because of three reasons: the duration of a distant event is elongated, the star formation rate (SFR) is high in the distant universe (e.g., Hopkins & Beacom 2006), and available optical facilities are numerous compared with X-ray/UV satellites. (2) A multiepoch imaging observation in a night is essential to draw the LCs of shock breakout in both rising and declining phases because the timescale of shock breakout in an SN II-P at z ≳ 2 is less than ~1 day in the observer frame (Section 3.2).

In the following, we estimate the expected number and highest redshift of detection, discuss influences of uncertainties on host galaxy extinction and SFH, and propose realistic and promising survey strategies, ways to identify shock breakout, and ways to constrain the SN properties from observable quantities. In this section, we focus on the models with E51 = 1 and Z = 0.02.

3.3.1. Expected Number

Host galaxy extinction heavily reduces the brightness of the shock breakout (Section 3.2), and thus it should be taken into account for a realistic number estimate. However, the host galaxy

![Figure 7. Apparent g'-band LCs of the models at z = 0.2 (red), z = 0.5 (green), z = 1 (blue), z = 1.5 (magenta), z = 2 (cyan), z = 2.5 (yellow), and z = 3 (black). No extinction and no IGM absorption are assumed. The panels are the same as in Figure 3. The horizontal line shows a 5σ detection limit in the g' band for the Subaru/Suprime-Cam 1 hr integration (gray, http://www.naoj.org/cgi-bin/spcam_tmp.cgi, assuming 0.7′′ seeing, 1.5′′ aperture, and 3 days from New Moon). (A color version of this figure is available in the online journal.)](image-url)
extinction of distant SNe II-P is unknown, but it will be clarified by future shock breakout studies. Hence, we expediently assume that the distribution of host galaxy extinction of distant SNe II-P is equivalent to that of nearby SNe II-P. The host galaxy extinction of a nearby SN II-P is estimated from the Na I D lines of the host galaxy, a spectroscopic observation of the SN, or the color of the SN plateau (e.g., Krisciunas et al. 2009; Olivares et al. 2010). We employ the distribution of host galaxy extinction in the F322W band for the JWST/NIRCam 10 s integration (gray, http://www.stsci.edu/jwst/instruments/nircam/sensitivity/index.html).

(A color version of this figure is available in the online journal.)
respectively. If $m_{x,\lim}$ are located (z = 0.05 (red), z = 0.1 (green), z = 0.15 (blue), z = 0.2 (magenta), z = 0.25 (cyan), and z = 0.3 (yellow)). No extinction and no IGM absorption are assumed. The panels are the same as in Figure 3. The horizontal line shows a 5σ detection limit in the NUV band for the GALEX satellite 1500 s integration (gray; Morrissey et al. 2007).

(A color version of this figure is available in the online journal.)

For example, the $g'$-band observations with $m_{g',\lim}$ = 20, 22, 24, 26, 27, 28, and 30 mag detect $3.1 \times 10^{-5}$, $6.2 \times 10^{-4}$, $1.4 \times 10^{-2}$, $3.7 \times 10^{-1}$, 1.7, 5.6, and 1.8 × 10° SNe deg$^{-2}$ day$^{-1}$, respectively. $n_e(m_{g',\lim})$ logarithmically increases with $m_{g',\lim}$ at $m_{g',\lim} \lesssim 27.5$ mag, but the increase slows down at $m_{g',\lim} \gtrsim 27.5$ mag because the maximum redshift of observable SNe reaches z $\sim$ 2.5 (Figures 13(a)–(m)) where the IGM absorption becomes non-negligible and the cosmic SFH hits a peak.

Redshifts below which a given fraction f of observable SNe are located (z$_{\pm, f}(m_{x,\lim})$, named “reachable redshift”) are shown in Figures 15(a)–(c). The fraction of high-z events increases with $m_{x,\lim}$. For example, the $g'$-band observations with $m_{g',\lim}$ = 20, 22, 24, 26, 27, 28, and 30 mag result in $[z_{g',0.0}(m_{g',\lim}), z_{g',0.5}(m_{g',\lim}), z_{g',0.9}(m_{g',\lim})] = (0.013, 0.027, 0.042), (0.035, 0.071, 0.11), (0.095, 0.19, 0.31), (0.26, 0.55, 1.0), (0.42, 0.96, 1.9), (0.62, 1.4, 2.4), and (0.90, 1.9, 3.0), respectively. If $m_{g',\lim} \gtrsim 27$ mag is realized, more than half of the observable SNe take place at z $\gtrsim$ 0.9. This capability to access high-z universe is an intriguing and unique feature of shock breakout.

If the same limiting magnitude is available, $n_x(m_{x,\lim})$ and $z_{x, f}(m_{x,\lim})$ of reddest bands are higher than those in redder bands at shallow $m_{x,\lim}$, e.g., $m_{x,\lim} \lesssim 24$–25 mag for UV, due to the blue SED of shock breakout. However, the increases in $n_x(m_{x,\lim})$ and $z_{x, f}(m_{x,\lim})$ for deep $m_{x,\lim}$ are suppressed by the IGM absorption. Therefore, $n_x(m_{x,\lim})$ and $z_{x, f}(m_{x,\lim})$ in redder bands overcome those in bluer bands for deep $m_{x,\lim}$. Thus, the most effective bandpass for shock breakout detection depends on feasible $m_{x,\lim}$. For example, the $g'$- and $r'$-band observations are currently the most effective in number and in reachable redshift, respectively, because only 8 m class optical telescopes or the Hubble Space Telescope ($m_{x,\lim} \lesssim 28$ mag) are available at the moment. When 30 m class optical/infrared telescopes ($m_{x,\lim} \sim 30$ mag) become operative, the most effective bands will be the $r'$ band in number and the $i'$ band in reachable redshift.

The reachable redshift dramatically increases if $m_{x,\lim}$ is deeper than 26–30 mag (Figures 13(a)–(m)) because the large negative $K$-correction makes the apparent peak magnitudes of shock breakout almost constant ($\sim$ 26–30 mag) for a wide redshift range (Figures 13(a)–(m)). Therefore, in order to detect distant shock breakout at z $\gtrsim$ 1, it is essential to attain $m_{x,\lim} \gtrsim 26$–30 mag. Since the dramatic increases of reachable redshift in optical bands coincide with the limiting magnitudes of current optical facilities, improvements in the near future will enhance the reachable redshift considerably. On the other hand, the increase in $z_{x,0.9}(m_{x,\lim})$ reaches the ceiling at z $\sim$ 4 for $m_{x,\lim} \sim 30$ mag even in NIR bands. This is because the
cosmic SFH in Hopkins & Beacom (2006) has low SFR at such a high redshift. It is important to note that the detection of shock breakout at $z > 4$ is feasible if an SFR is high enough, unless the bandpass is below the rest-frame Lyα wavelength.

According to $n_s(m_x, \text{lim})$, observable SN rates per unit time $\Omega_{\text{obs}} n_s(m_x, \text{lim})$ with a given $m_x, \text{lim}$ and a survey area $\Omega_{\text{obs}}$ are shown in Figures 16(a) and (b). An observation in a bluer band is more efficient with the same $m_x, \text{lim}$ if a wide survey area is available ($\geq 1\, \text{deg}^2$), while an observation in a redder band is slightly better if only a narrow survey area observation ($<0.1\, \text{deg}^2$) with deep $m_x, \text{lim}$ ($\geq 30\, \text{mag}$) is available. The flat dependence of $\Omega_{\text{obs}} n_s(m_x, \text{lim})$ on $m_x, \text{lim}$ at deep $m_x, \text{lim}$, e.g., $m_{g, \text{lim}} \gtrsim 28\, \text{mag}$ in the $g'$ band, stems from the suppression of $n_s(m_x, \text{lim})$ by the IGM absorption and the low SFR at high redshift.

Figure 16(b) shows lines giving equal $\Omega_{\text{obs}} n_g(m_{g, \text{lim}})$ with the $g'$-band observation. The gray lines represent equal survey powers without taking into account observing overhead such as readout time. The number of observable SNe is larger for wider and shallower observations with a given survey power. However, such a wide and shallow observation misses high-$z$ events (Figures 15(a)–(c)), and $\Omega_{\text{obs}} n_g(m_{g, \text{lim}})$ has an upper limit if the overhead is taken into account. Therefore, the practical survey parameters should be customized to purposes of observations and adopted telescopes/instruments, considering the number, reachable redshift, and overhead.

3.3.2. Dependencies on Host Galaxy Extinction and Star Formation History

We set the above estimate with the SFH in Hopkins & Beacom (2006) and our Galaxy extinction law (HB06-Gal) as a control estimate and investigate the dependence of $n_s(m_x, \text{lim})$ on uncertainties of host galaxy extinction and SFH (Figure 14(b)).

We attempt Large Magellanic Cloud and Small Magellanic Cloud extinction laws (estimates HB06-LMC and HB06-SMC; Pei 1992) for host galaxies. The LMC and SMC extinction laws have larger absorption at $\lambda < 2000\, \text{Å}$ and smaller at $\lambda \sim 2200\, \text{Å}$ in the rest frame than our Galaxy extinction law. As a result, $n_g(m_{g, \text{lim}})$ of estimates HB06-LMC and HB06-SMC are slightly smaller at $m_{g, \text{lim}} \gtrsim 27\, \text{mag}$ than that of estimate HB06-Gal, but the estimates HB06-Gal, HB06-LMC, and HB06-SMC are similar at $m_{g, \text{lim}} \lesssim 26\, \text{mag}$.

The SFH in Hopkins & Beacom (2006) is derived by scaling UV SFH so as to be consistent with infrared SFH and thus presumably includes both visible and dust-obscured star formation. Although we correct the dust extinction in host galaxies, it could underestimate the host galaxy extinction. Additionally, some studies suggest that Hopkins & Beacom (2006) overcorrect the dust extinction and overestimate the SFR.
by a factor of $\sim 2$ at $z \sim 2-3$ (e.g., Nagashima & Yoshii 2004; Nagashima et al. 2005; Baugh et al. 2005; Lacey et al. 2011). Hence, we test with UV dust-unobscured SFH (Mannucci et al. 2007). Although their estimate is limited at $z < 2$, the SFR at $z > 2$ is assumed to be the same as the SFR at $z = 2$. Since the dust attenuation of shock breakout brightness in a host
We also investigate the dependencies of $z_{g',f}(m_{g',\text{lim}})$ on host galaxy extinction and SFH (Figure 15(c)). $z_{g',0.9}(m_{g',\text{lim}})$ of the estimates HB06-Gal and MDPO7-Gal are consistent but they are slightly lower than the estimate MDPO7-no at $m_{g',\text{lim}} > 26$ mag and the estimate MK11-Gal at $m_{g',\text{lim}} < 25$ mag. And the estimate HB06-LMC has slightly higher $z_{g',0.9}(m_{g',\text{lim}})$ at $m_{g',\text{lim}} < 25$ mag than the estimate HB06-Gal, while $z_{g',0.9}(m_{g',\text{lim}})$ of the estimate HB06-LMC at $m_{g',\text{lim}} > 27$ mag and the estimate HB06-SMC are consistent with that of the estimate HB06-Gal. These are because $z_{s,f}(m_{\text{r,lim}})$ depends mainly on the host galaxy extinction at shallow $m_{\text{r,lim}}$ and the IGM absorption at deep $m_{\text{r,lim}}$. The reason why $z_{s,0.9}(m_{\text{r,lim}})$ of the estimate MDPO7-Gal is higher than that of the estimate HB06-Gal at $m_{\text{r,lim}} > 31$ mag is because we assume constant SFR at high redshift in the estimate MDPO7-Gal, which is higher than the SFR in Hopkins & Beacom (2006) at $z > 5$.

3.3.3. Requirements on Survey Strategies

Although the above estimates refer only to the peak apparent magnitude, the cadence of observations is also an important ingredient to identify transients. Indeed, it is difficult to identify and interpret an event with only one-epoch brightening. Additionally, the above estimates do not take into account an elongation of the duration at high redshift. Hence, we estimate the number of detections of shock breakout $N_{\text{r,t}}(m_{\text{r,lim}}, \Omega_{\text{obs}})$

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Figure 13. Peak $g'$ magnitude $m'_{g,\text{peak}}$ and distance modulus (black) as a function of redshift. The peak magnitudes are derived by assuming no extinction and IGM absorption (red), host galaxy extinction ($E(B - V)_{\text{host}} = 0.1$ mag and our Galaxy extinction law as a lower limit (estimate MDPO7-Gal)).

We present an estimate with no additional host galaxy extinction and dust extinction of each galaxy are provided, the SFH estimate is free from uncertainties of extinction correction and conversion from the galaxy luminosity to the SFR.

We also investigate the dependencies of $z_{g',f}(m_{g',\text{lim}})$ on host galaxy extinction and SFH (Figure 15(c)). $z_{g',0.9}(m_{g',\text{lim}})$ of the estimates HB06-Gal and MDPO7-Gal are consistent but they are slightly lower than the estimate MDPO7-no at $m_{g',\text{lim}} > 26$ mag and the estimate MK11-Gal at $m_{g',\text{lim}} < 25$ mag. And the estimate HB06-LMC has slightly higher $z_{g',0.9}(m_{g',\text{lim}})$ at $m_{g',\text{lim}} < 25$ mag than the estimate HB06-Gal, while $z_{g',0.9}(m_{g',\text{lim}})$ of the estimate HB06-LMC at $m_{g',\text{lim}} > 27$ mag and the estimate HB06-SMC are consistent with that of the estimate HB06-Gal. These are because $z_{s,f}(m_{\text{r,lim}})$ depends mainly on the host galaxy extinction at shallow $m_{\text{r,lim}}$ and the IGM absorption at deep $m_{\text{r,lim}}$. The reason why $z_{s,0.9}(m_{\text{r,lim}})$ of the estimate MDPO7-Gal is higher than that of the estimate HB06-Gal at $m_{\text{r,lim}} > 31$ mag is because we assume constant SFR at high redshift in the estimate MDPO7-Gal, which is higher than the SFR in Hopkins & Beacom (2006) at $z > 5$.

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for an observation sampling \( i \) with bandpass \( x \), \( m_{x,\text{lim}} \), and a field of view \( \Omega_{\text{obs}} \), which can be obtained by an integration of a "control time" \( \Gamma_{i,x}(M_{\text{MS}}, A_V, z, m_{x,\text{lim}}) \)\(^{21} \) as follows:

\[
N_{i,x}(m_{x,\text{lim}}, \Omega_{\text{obs}}) = \int \int \Gamma_{i,x}(M_{\text{MS}}, A_V, z, m_{x,\text{lim}}) \phi(M_{\text{MS}}) 
\times \Omega_{\text{obs}} \frac{dV(z)}{d\Omega dz} \frac{\eta(z)\chi(A_V) dM_{\text{MS}} dz dA_V}{1 + z},
\]

which is similar to Equation (2) but integrates with \( \Gamma_{i,x}(M_{\text{MS}}, A_V, z, m_{x,\text{lim}}) \) instead of \( f_x[m_{\text{peak}, x}(M_{\text{MS}}, A_V, z, m_{x,\text{lim}})] \). We define the detection with two criteria: (1) the event is detected at \( \geq N_{\text{detect}} \) samplings with \( \sigma \) and (2) at least one of samplings is taken from \( t_{\text{obs}} = -0.2 \) days to \( t_{\text{obs}} = 0.4 \) days. \( \Gamma_{i,x}(M_{\text{MS}}, A_V, z, m_{x,\text{lim}}) \) is determined by simulating the detection of shock breakouts. The expected number of detections and reachable redshift are slightly smaller and lower, respectively, than the previous estimates in which all events with \( m_{\text{peak}, x} \leq m_{x,\text{lim}} \) are counted because we require a detectable SN to be brighter than \( m_{x,\text{lim}} \) over \( \geq N_{\text{detect}} \) samplings.

We attempt strategies A–N which divide a 6, 12, or 18 hr \( g' \)-band observation with respective ways, assuming the cosmic SFH in Hopkins & Beacom (2006) and our Galaxy extinction law (Pei 1992). Here, we treat the number of nights \( N_{\text{night}} \), observation sampling per night \( n_{\text{obs}} \), and exposure time for each sampling \( t_{\exp} \), as parameters, assume \( N_{\text{detect}} = 3 \), and adopt measurements from the Subaru/Suprime-Cam to estimate \( m_{x,\text{lim}} \) for \( 3\sigma \) detection (Miyazaki et al. 2002). Each observation sampling is uniformly distributed throughout the entire night (10 hr for each night) and an overhead is neglected. The detail of strategies and the results, the expected number per square degree, and the redshift below which 90% of events occur, are summarized in Table 3.

While large \( N_{\text{night}} \) enhances the number of detection, large \( n_{\text{obs}} \), and long \( t_{\exp} \) enhance the reachable redshift. For the same \( N_{\text{night}} \), a strategy with \( n_{\text{obs}} = 5 \), in which a field is observed every 2 hr, is the most efficient in number and reachable redshift.

The remarkably small number of detections of strategy L (\( n_{\text{obs}} = 1 \)) demonstrates that multiple photometric observations in a night are essential to detect shock breakout because shock breakout brightens and declines within \( \sim 1 \) day. Comparing the strategies A, M, and N, an additional one night observation increases the number of detections by \( 2.3 \) deg\(^{-2}\), which is larger than the number of detections for the one night observation (1.6 deg\(^{-2}\), strategy A). This is because the observation over \( \geq 2 \) continuous nights can detect an event, taking place at
the SN rate per day \( \Omega_{\text{obs}} n_x(m_{x,\text{lim}}) \) as a function of limiting magnitude \( m_{x,\text{lim}} \), and survey area \( \Omega_{\text{obs}} \). (a) \( \Omega_{\text{obs}} n_x(m_{x,\text{lim}}) \) in different bandpass: the colors are the same as in Figure 14(a) and (b) different \( \Omega_{\text{obs}} n_x(m_{x,\text{lim}}) \) in the \( g' \) band: \( \Omega_{\text{obs}} n_x(m_{x,\text{lim}}) = 0.01 \) (red), 0.1 (green), 1 (blue), 10 (magenta), 100 (cyan), \( 10^3 \) (black), and \( 10^5 \) (orange). The lines being accessible by equal survey powers are shown (gray).

(A color version of this figure is available in the online journal.)

### Table 3

| Strategy | \( N_{\text{night}} \) [nights] | \( n_{\text{obs}} \) [night\(^{-1}\)] | \( t_{\exp} \) [min] | \( m_{x,\text{lim}} \) [(mag)] | Number\(^b\) \( \Omega_{\text{obs}} \) \( n_x(m_{x,\text{lim}}) \) [(deg\(^{-2}\)] | Reachable Redshift\(^c\) | Number With Overhead\(^d\) [(deg\(^{-2}\)] |
|----------|-------------------------------|----------------------------------|-----------------|-----------------|-------------------------------------------|------------------|------------------|
| A        | 1                            | 3                               | 120             | 28.4            | 1.56                                       | 2.40             | 1.42             |
| B        | 2                            | 3                               | 60              | 28.0            | 2.62                                       | 2.21             | 2.38             |
| C        | 4                            | 3                               | 30              | 27.6            | 3.57                                       | 1.99             | 3.25             |
| D        | 12                           | 3                               | 10              | 27.1            | 4.66                                       | 1.46             | 4.23             |
| E        | 24                           | 3                               | 5               | 26.7            | 5.22                                       | 1.07             | 4.75             |
| F        | 40                           | 3                               | 3               | 26.4            | 5.49                                       | 0.84             | 4.70             |
| G        | 60                           | 3                               | 2               | 26.2            | 5.81                                       | 0.71             | 4.65             |
| H        | 2                            | 4                               | 45              | 27.9            | 2.71                                       | 2.25             | 2.46             |
| I        | 2                            | 5                               | 36              | 27.8            | 2.73                                       | 2.25             | 2.49             |
| J        | 2                            | 6                               | 30              | 27.6            | 2.71                                       | 2.25             | 2.46             |
| K        | 2                            | 12                              | 15              | 27.3            | 2.31                                       | 2.12             | 2.10             |
| L        | 3                            | 1                               | 120             | 28.4            | 0.0651                                     | 2.44             | 0.0592           |
| M        | 2                            | 3                               | 120             | 28.4            | 3.91                                       | 2.35             | 3.55             |
| N        | 3                            | 3                               | 120             | 28.4            | 6.26                                       | 2.34             | 5.70             |

Notes.

\( a \) The limiting magnitude is calculated with Subaru Imaging Exposure Time Calculator (http://www.naoj.org/cgi-bin/spcam_tmp.cgi) assuming 0.7 seeing, 1.5 aperture, and 3 days from New Moon.

\( b \) The number of observable SNe in total, assuming no overhead.

\( c \) The redshift below which 90% of observable SNe occur.

\( d \) The number of observable SNe reduced in proportion to the overhead, 10% for \( t_{\exp} \geq 5 \) minutes and 30 s for \( t_{\exp} < 5 \) minutes.

SNe taking into account an overhead. Here, we expeditiously assume an overhead as 10% of the total observation for \( t_{\exp} \geq 5 \) minutes or 30 s for \( t_{\exp} < 5 \) minutes and reduce the number of observable SNe in proportion to the fraction of overhead. As a result, the number of observable SNe peaks at \( t_{\exp} = 5 \) minutes for this specific overhead.

#### 3.3.4. Identification of Shock Breakout

Many transients other than shock breakouts, e.g., variable stars, SNe, quasars (QSOs), and GRBs, will be found as variable objects in a photometric observation. Shock breakouts can be reliably discriminated from other kinds of variable objects by holistically referring to observable quantities: timescale, LC shape, color, and position, and other observations.

**Timescale and LC shape.** Shock breakouts have a nonrecurrent brightening, a timescale of several seconds to several days, and a featureless LC. On the other hand, (1) SNe powered by radioactive decays, the plateau of SNe II-P or Type IIb SNe, or linear decay of Type II-L SNe have timescales of tens of days to several hundred days, (2) GRB optical flash has a timescale of tens of seconds and frequently has jagged multiple peaks (e.g., Woźniak et al. 2009), and (3) the flare of a low-mass star, e.g., an M dwarf star, has a timescale of several minutes to several hours and recurrent brightening (e.g., Hawley et al. 2003). Therefore, the timescale and LC shape of a transient can be employed for excluding these objects.

**Position, archival image, and other observations.** If a survey is performed at fields with plenty of past observations, checking past variabilities at the position can effectively rule out possibilities of long timescale variables such as QSOs or variable stars. If the event occurs in the outskirts of the host galaxy or is not detected in X-ray, the variable object is likely to be a shock breakout.\(^{22}\) And the deep UV, optical, and infrared imaging data are also useful for excluding the possibility of stars.

\( ^{22} \) Some low-luminosity active galactic nuclei at high redshift cannot be detected even in deep X-ray data (Sarajedini et al. 2006; Cohen et al. 2006; Morokuma et al. 2008).
Furthermore, if the field is included in the field of view of γ-ray telescope (e.g., Swift/BAT; Gehrels et al. 2004), an alert of GRB can be used for ruling out a possibility of a GRB. Even if the GRB prompt emission cannot be observed (i.e., the GRB orphan afterglows), a radio follow-up observation can constrain the presence of relativistic jets (e.g., Soderberg et al. 2008, 2010).

Color. The conclusive identification of a shock breakout is given by the color of a variable. Figures 17(a)–(f) (u′ − g′ versus g′ − r′) and 18(a)–(f) (g′ − r′ versus r′ − i′) show redshift-dependent color–color diagrams for the less massive 15 M⊙ and E51 = 1 model, massive 25 M⊙ and E51 = 1 model, and energetic 25 M⊙ and E51 = 10 model taking into account the IGM absorption (Madau 1995) and compare them with color–color distributions of stars and QSOs (Schneider et al. 2002, 2003, 2005, 2007, 2010) for Figures 17(a)–(f) and 18(a)–(f) and with colors derived from typical spectra (stars: Bruzual–Persson–Gunn–Stryker atlas; Strecker et al. 1979; Gunn & Stryker 1983; and QSOs: Vanden Berk et al. 2001) for Figures 19(a)–(f) and 20(a)–(f). Here, these figures show extinction-corrected colors of stars and extinction-corrected colors of QSOs at z ± Δz (where Δz = 0.1(1 + z), being an accuracy of a photometric redshift). Ordinary SNe are not likely to have a red color in optical bands. Also the color is realized at t ≳ 1 days (see also Figures 11(a)–(m)), except for u′ − g′ at z ≳ 2.5 or g′ − r′ at z ≳ 3. These exceptions stem from the fact that the light in the observed u′ and g′ bands are heavily absorbed by the IGM at z ≳ 2.5 and z ≳ 3, respectively. The color of shock breakout is much bluer than the majorities of stars and QSOs but we note that the color at t = 0 is similar to O/B stars and that the NIR colors of less massive and energetic models at tobs = 2 days and massive model at tobs = 10 days are similar to QSOs.

GRB orphan afterglow and M dwarf flare could have a similar timescale, featureless LC, and noncurrent brightening in a limited-time photometric observation. However, the blue color is a precise identifier of shock breakout. According to a standard model for GRB afterglow (e.g., Sari et al. 1998), GRB afterglow is red at a frequency range above frequencies corresponding to the minimum or cooling Lorentz factor. Adopting reasonable parameters for GRBs (e.g., Panaitescu & Kumar 2002), the minimum or cooling frequency at z ≳ 0.1 days after the prompt burst is ν ≲ 1014 Hz and thus the red color is realized at λ ≳ 3 × 104 Å. Although the minimum and cooling frequencies are higher for earlier epochs, the GRB orphan afterglow will typically peak at >0.1 days (e.g., Totani & Panaitescu 2002). Therefore, the GRB orphan afterglow is likely to have a red color in optical bands. Also the color of a low-mass star flare is typically red (e.g., Kowalski et al. 2009).

3.3.5. Constraints on Supernova Properties from Shock Breakout

SN properties can be constrained from the observations of the shock breakout. Here, we focus on three observational quantities: peak magnitude, decline rate, and color evolution. Their dependencies on the model properties, MMS, LpreSN, and E, at z = 0.2, z = 1, and z = 2 are summarized in Tables 4–6 and shown in Figures 21(a)–(c), 22(a)–(i), and 23(a)–(i), respectively. Here, we assume that the redshift of the shock breakout is determined photometrically or spectroscopically. Figures 21(a)–(c), 22(a)–(c), and 23(a)–(c) show the apparent peak g′-band magnitude mpeak,g′, peak vary over ∼1.5–2 mag depending on RpreSN and thus MMS, although Lpeak are similar for the models with E51 = 1 (Figure 6(a)). On the other hand, although Lpeak varies by an order of magnitude depending on E (Figure 6(b)), the mpeak,g′ range of the models with different E is only ∼0.7 mag. The different behavior between bolometric and monochromatic luminosities stems from the different photospheric temperatures, leading to different values of Tc. The models with larger RpreSN have lower temperature.

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23 Photometrically identified stars with photometric errors < 0.01 mag are extracted from the Seventh Data Release (DR7; Abazajian et al. 2009) of the Sloan Digital Sky Survey (SDSS; York et al. 2000). The number of stars is over 4 × 106. We note that the sample could be biased toward bright and thus blue stars because the stars with small errors are selected.

24 http://www.stsci.edu/hst/observatory/cdbs/astrophysical_catalogs.html
Figure 18. Color–color ($g' - r' \text{ vs. } r' - i'$) diagrams for the models at various redshifts. The panels, contours, points, lines, and arrows are the same as in Figure 17 but $A_V = 0.5 \text{ mag}$ is assumed for the extinction vectors of host galaxies. (A color version of this figure is available in the online journal.)

Figure 19. Color–color (FUV – NUV vs. $g' - r'$) diagrams of the models at (a) $z = 0.05$, (b) $z = 0.1$, (c) $z = 0.15$, (d) $z = 0.2$, (e) $z = 0.25$, and (f) $z = 0.3$. The points without lines represent colors of stars (cyan, Bruzual–Persson–Gunn–Stryker atlas; Strecker et al. 1979; Gunn & Stryker 1983) and QSOs (magenta; Vanden Berk et al. 2001). The colors of QSOs are represented by open triangles when the rest-frame Ly $\alpha$ wavelength is redshifted into FUV band. The color of lines, points on lines, and arrows are the same as in Figure 17 but $A_V = 0.5 \text{ mag}$ is assumed for the extinction vectors of host galaxies. (A color version of this figure is available in the online journal.)

and thus redder SEDs and are slightly brighter at $\lambda \gtrsim 300 \text{ Å}$ (Figure 4(a)), while the models with higher $E$ have higher temperature and thus bluer SEDs but the luminosities are almost similar at $\lambda \gtrsim 800 \text{ Å}$ (Figure 4(b)). We note that the $g'$-band luminosities peak at $t_{\text{obs}} \sim 0.001–0.05 \text{ days}$ because of the temperature evolution (see also Figures 7(a)–(m)).

Figures 21(d)–(f), 22(d)–(f), and 23(d)–(f) show days after the $g'$-band peak until the $g'$-band magnitude declines by $0.5 \text{ mag } t_{g', 0.5 \text{ mag}}$. The dependencies of the decline rate in $g'$ band on $R_{\text{preSN}} (M_{\text{MS}})$ and $E$ are almost similar to those in the bolometric LC. This is because the decline rate depends on energetics of SNe but not on the temperature when the SED peaks at shorter $\lambda$ than the $g'$ band. Since the dependencies of $m_{g', \text{peak}}$ and $t_{g', 0.5 \text{ mag}}$ on $R_{\text{preSN}} (M_{\text{MS}})$ and $E$ are different, in principal they could determine $R_{\text{preSN}} (M_{\text{MS}})$ and $E$ independently.

However, apparent brightness is dimmed by extinction and thus results in large uncertainties. Hence, we introduce the color evolution to resolve the uncertainties. Although the absolute color is also strongly reddened by extinction, the color evolution does not suffer from extinction unless extinction changes with time. Figures 21(g)–(o), 22(g)–(i), and 23(g)–(i) show the color evolutions, FUV – NUV, $u' - g'$, and $g' - r'$ for $z = 0.2$ and $g' - r'$ for $z = 1$ and $z = 2$, respectively (see also Figures 11(a)–(m)). These figures show the bluest color, that is realized at $t_{\text{color}} = 0$ corresponding to $t_{\text{obs}} \sim 0.03–0.2 \text{ days}$, and the colors at $t_{\text{color}} = 0.5, 1,$ and $2 \text{ days}$, where color is
Figure 20. Color–color ($J-H$ vs. $H-K$) diagrams of the models at various redshifts. The panels, color of lines, points, and arrows are the same as in Figure 19 but $A_V = 3$ mag is assumed for the extinction vectors of host galaxies.

(A color version of this figure is available in the online journal.)

Table 4
Observable Quantities at $z = 0.2$

| $M_{MS}$ ($M_\odot$) | $Z$ | $E$ ($10^{51}$ erg) | $m^{\prime}_{peak}$ (mag) | $t^{\prime}_{0.5\text{mag}}$ (0.01 days) | FUV − NUV (mag) | $u^{\prime} - g^{\prime}$ (mag) | $g^{\prime} - r^{\prime}$ (mag) |
|----------------------|-----|---------------------|--------------------------|------------------------------------------|-----------------|--------------------------|--------------------------|
|                      |     |                     |                          |                                           | $t^{\text{obs}}_{\text{FUV-NUV}} = 0$ | $t^{\text{obs}}_{\text{FUV-NUV}} = 2$ days | $t^{\text{obs}}_{\text{FUV-NUV}} = 0$ | $t^{\text{obs}}_{\text{FUV-NUV}} = 2$ days |
| 13                   | 0.02 | 1                   | 24.31                    | 2.27                                     | −0.668          | −0.371                   | −0.568                   | −0.292                   | −1.45                   | −0.0750                  |
| 15                   | 0.02 | 1                   | 24.50                    | 1.89                                     | −0.683          | −0.381                   | −0.580                   | −0.290                   | −1.49                   | −0.173                   |
| 18                   | 0.02 | 1                   | 23.94                    | 3.25                                     | −0.658          | −0.337                   | −0.556                   | −0.281                   | −1.41                   | −0.00539                 |
| 20                   | 0.02 | 1                   | 23.76                    | 3.85                                     | −0.645          | −0.335                   | −0.545                   | −0.285                   | −1.38                   | −0.0692                  |
| 25                   | 0.02 | 1                   | 23.12                    | 7.28                                     | −0.599          | −0.386                   | −0.507                   | −0.308                   | −1.24                   | −0.185                   |
| 30                   | 0.02 | 1                   | 22.92                    | 7.81                                     | −0.403          | −0.403                   | −0.502                   | −0.314                   | −1.23                   | −0.235                   |
| 40                   | 0.02 | 1                   | 22.60                    | 13.6                                     | −0.553          | −0.430                   | −0.463                   | −0.352                   | −1.17                   | −0.468                   |
| 25                   | 0.02 | 4                   | 22.80                    | 6.46                                     | −0.580          | −0.357                   | −0.495                   | −0.299                   | −1.30                   | −0.499                   |
| 25                   | 0.02 | 10                  | 22.60                    | 6.42                                     | −0.561          | −0.424                   | −0.485                   | −0.322                   | −1.31                   | −0.921                   |
| 25                   | 0.02 | 20                  | 22.43                    | 6.46                                     | −0.541          | −0.446                   | −0.469                   | −0.356                   | −1.29                   | −1.11                    |
| 20                   | 0.001| 1                   | 23.96                    | 4.81                                     | −0.661          | −0.325                   | −0.557                   | −0.279                   | −1.39                   | −0.0328                  |
| 20                   | 0.004| 1                   | 23.89                    | 3.66                                     | −0.657          | −0.329                   | −0.555                   | −0.276                   | −1.39                   | −0.0569                  |
| 20                   | 0.05 | 1                   | 23.26                    | 6.15                                     | −0.610          | −0.359                   | −0.513                   | −0.303                   | −1.28                   | −0.152                   |

Table 5
Observable Quantities at $z = 1$

| $M_{MS}$ ($M_\odot$) | $Z$ | $E$ ($10^{51}$ erg) | $m^{\prime}_{peak}$ (mag) | $t^{\prime}_{0.5\text{mag}}$ (0.01 days) | $u^{\prime} - g^{\prime}$ (mag) | $g^{\prime} - r^{\prime}$ (mag) |
|----------------------|-----|---------------------|--------------------------|------------------------------------------|-----------------|--------------------------|--------------------------|
|                      |     |                     |                          |                                           | $t^{\text{obs}}_{\text{FUV-NUV}} = 0$ | $t^{\text{obs}}_{\text{FUV-NUV}} = 2$ days | $t^{\text{obs}}_{\text{FUV-NUV}} = 0$ | $t^{\text{obs}}_{\text{FUV-NUV}} = 2$ days |
| 13                   | 0.02 | 1                   | 27.01                    | 4.58                                     | −0.534          | −0.156                   |
| 15                   | 0.02 | 1                   | 27.17                    | 3.67                                     | −0.548          | −0.156                   |
| 18                   | 0.02 | 1                   | 26.66                    | 6.18                                     | −0.521          | −0.165                   |
| 20                   | 0.02 | 1                   | 26.50                    | 7.39                                     | −0.511          | −0.201                   |
| 25                   | 0.02 | 1                   | 25.94                    | 12.8                                     | −0.464          | −0.290                   |
| 30                   | 0.02 | 1                   | 25.74                    | 14.3                                     | −0.461          | −0.299                   |
| 40                   | 0.02 | 1                   | 25.48                    | 24.7                                     | −0.419          | −0.308                   |
| 25                   | 0.02 | 4                   | 25.59                    | 11.5                                     | −0.460          | −0.202                   |
| 25                   | 0.02 | 10                  | 25.41                    | 11.0                                     | −0.457          | −0.290                   |
| 25                   | 0.02 | 20                  | 25.26                    | 7.67                                     | −0.446          | −0.360                   |
| 20                   | 0.001| 1                   | 26.69                    | 9.39                                     | −0.523          | −0.198                   |
| 20                   | 0.004| 1                   | 26.62                    | 6.96                                     | −0.519          | −0.193                   |
| 20                   | 0.05 | 1                   | 26.06                    | 11.1                                     | −0.471          | −0.271                   |
Figure 21. Dependencies of observational quantities on the model properties, $M_{\text{MS}}, R_{\text{preSN}},$ and $E,$ at $z = 0.2.$ The color of symbols represents $Z = 0.02$ models (red); $M_{\text{MS}} = 20 M_\odot$ models with $Z = 0.001, 0.004,$ and 0.05 (blue); and $M_{\text{MS}} = 25 M_\odot$ models with $E_{51} = 1, 4, 10,$ and 20 (green). (g–o) The colors of the models at $t_{\text{color}}^{\text{obs}} = 0$ (filled circles), 0.5 days (open square), 1 day (open triangles), and 2 days (open circles).

(A color version of this figure is available in the online journal.)

FUV – NUV, $u' - g',$ or $g' - r'.$ The colors of some models evolve toward red at first and then get back to blue again, which is shown as a loop structure in Figures 17(a)–(f), 18(a)–(f), 19(a)–(f), and 20(a)–(f).

The model with smaller $R_{\text{preSN}}$ has a bluer color at the peak because of the higher temperature and its color evolution is more rapid. The color evolution within 2 days are $\Delta(g' - r') \gtrsim 0.3$ mag for the model with $R_{\text{preSN}} < 10^3 R_\odot$ and $\Delta(g' - r') \lesssim 0.25$ mag.
Days for 0.5 mag decline in the g' band
tg',0.5mag [days]

Peak g'-band magnitude
mg',peak [mag]

Main-sequence Mass MMS [M]

Presupernova radius RpreSN [R]

Explosion energy E [10^{51} erg]

Figure 22. Same as Figure 21, but for z = 1.

(A color version of this figure is available in the online journal.)

Table 6
Observable Quantities at z = 2

| M_{MS} (M_{\odot}) | Z    | E (10^{51} erg) | mg',peak (mag) | t_{g'0.5mag} (0.01 days) | g'−r' (mag) t_{obs}' = 0 | g'−r' (mag) t_{obs}' = 2 days |
|---------------------|------|----------------|----------------|---------------------------|--------------------------|-----------------------------|
| 13                  | 0.02 | 1              | 27.84          | 7.08                      | −0.428                   | −0.107                      |
| 15                  | 0.02 | 1              | 27.99          | 5.71                      | −0.440                   | −0.077                      |
| 18                  | 0.02 | 1              | 27.50          | 9.11                      | −0.415                   | −0.119                      |
| 20                  | 0.02 | 1              | 27.34          | 10.8                      | −0.408                   | −0.117                      |
| 25                  | 0.02 | 1              | 26.83          | 19.1                      | −0.371                   | −0.154                      |
| 30                  | 0.02 | 1              | 26.65          | 20.6                      | −0.366                   | −0.164                      |
| 40                  | 0.02 | 1              | 26.39          | 34.8                      | −0.355                   | −0.210                      |
| 25                  | 0.02 | 4              | 26.45          | 15.2                      | −0.393                   | −0.193                      |
| 25                  | 0.02 | 10             | 26.28          | 13.8                      | −0.395                   | −0.304                      |
| 25                  | 0.02 | 20             | 26.13          | 9.92                      | −0.391                   | −0.429                      |
| 20                  | 0.001| 1              | 27.53          | 13.7                      | −0.413                   | −0.125                      |
| 20                  | 0.004| 1              | 27.46          | 10.3                      | −0.412                   | −0.123                      |
| 20                  | 0.05 | 1              | 26.94          | 16.2                      | −0.383                   | −0.156                      |

for the model with R_{preSN} > 10^{3} R_{\odot}. For example, the 13 M_{\odot} model has a redder color than the 30 M_{\odot} model at $t_{\text{color}} = 1$ day for $z = 0.2$ and at $t_{\text{obs}}' = 2$ days for $z = 1$ and $z = 2$. On the other hand, the bluest colors of models with different $E$ are similar but the models with higher $E$ have more rapid and smaller variations. The color evolutions of the models with different $Z$ are similar to those of the $Z = 0.02$ models with the same $R_{\text{preSN}}$ and thus could cause uncertainty for constraining $M_{MS}$ when the metallicity of host galaxy is unknown. In conclusion, the color evolutions can classify shock breakouts, at least, into the following three groups: explosions with $R_{\text{preSN}} < 10^{3} R_{\odot}$ and $R_{\text{preSN}} > 10^{3} R_{\odot}$ ($M_{MS} \lesssim 20 M_{\odot}$ and $M_{MS} \geq 25 M_{\odot}$).
for the $Z = 0.02$ models) and an energetic explosion with $E_{51} \geq 10$.

4. CONCLUSIONS AND DISCUSSION

Shock breakout is the brightest event in the SN with a shockwave and could consummate the detection of CCSNe in the high-$z$ universe. We present multicolor LCs of shock breakouts in SNe II-P with various $M_{\text{MS}}$, $Z$, and $E$ based on realistic stellar models. Using our theoretical models, we investigate the dependencies of shock breakout properties on the progenitors and explosion energies and present thorough prospects for future surveys of shock breakouts. It is essential for identifying and interpreting shock breakouts to observe a field more than once in a night in multiple blue optical bands, preferably over $\geq 2$ continuous nights. And, adopting standard cosmic SFH, IMF, extinction distribution of host galaxies, the $g'$-band observable SN rate for $m_{g',\text{lim}} = 27.5\text{ mag}$ is $3.3\text{ SNe deg}^{-2}\text{ day}^{-1}$ and half of them are located at $z \geq 1.2$.

We calculate 13 SN models with $M_{\text{MS}} = 13$–40 $M_\odot$, $Z = 0.001$–0.05, and $E_{51} = 1$–20 (Table 2). The model with larger $R_{\text{preSN}}$, thus typically larger $M_{\text{MS}}$, has lower $T_{\text{c,peak}}$, $t_{1\text{mag}}$, and higher $E_{\text{rad,1mag}}$, while the model with higher $E$ has higher $T_{\text{c,peak}}$, $E_{\text{rad,1mag}}$, and $L_{\text{peak}}$. The metallicity affects shock breakout mainly through altering the stellar structure. The variations of $T_{\text{c,peak}}$, $t_{1\text{mag}}$, $E_{\text{rad,1mag}}$, and $L_{\text{peak}}$ among the adopted models are $\sim(2$–5) $\times 10^5\text{ K}$, $\sim$0.01–0.6 days, $\sim(0.7$–5) $\times 10^{48}\text{ erg}$, and $\sim(0.5$–7) $\times 10^{44}\text{ erg s}^{-1}$, respectively. The dependencies of numerical results are similar to those of the semi-analytical solutions (Matzner & McKee 1999). The semi-analytical solutions are nearly consistent with the numerical results if $T_{\text{MM99}}$, $E_{\text{MM99}}$, $t_{\text{MM99}}$, and $L_{\text{MM99}}$ are reduced by factors of 1.5, 3, 2, and 1.5, respectively.

According to the models, we predict the observational quantities of high-$z$ shock breakout. Since shock breakout has a blue SED peaked at $\sim 100\text{ Å}$, brightness of shock breakout at a fixed observed bandpass is less dimmed compared to the geometrical dilution, i.e., shock breakout has a large negative $K$-correction. This makes it possible to detect high-$z$ shock breakout, e.g., up to $z \sim 3.5$ in $g'$ band with 8 m class telescopes if there is no extinction in the host galaxy. Although shock breakout strongly suffers from the extinction and IGM absorption, it can be detected up to $z \sim 2$ if the host galaxy has the color excess $E(B-V)_{\text{host}} = 0.1\text{ mag}$ and our Galaxy extinction law.

Convolving the Salpeter’s IMF, cosmic SFH, host galaxy extinction, and IGM absorption, we estimate the observable SN rate as a function of bandpass and limiting magnitude. As a result, considering the operative telescopes/instruments, the $g'$-band observation is currently the most effective for the number of detections. Adopting cosmic SFH by Hopkins & Beacom (2006) and our Galaxy extinction law, the observable SN rate is $3.3\text{ SNe deg}^{-2}\text{ day}^{-1}$ for $m_{g',\text{lim}} = 27.5\text{ mag}$. Even taking

![Figure 23. Same as Figure 21, but for $z = 2$.](A color version of this figure is available in the online journal.)
into account uncertainties on host galaxy extinction and SFH, the observable SN rate is $\geq 0.93 \text{ SNe deg}^{-2} \text{ day}^{-1}$.

We also present the redshift distribution of observable SNe. For currently available $m_{\text{lim}} = 27.5 \text{ mag}$, 50% of observable SNe take place at $z \geq 1.2$. Furthermore, for $m_{\text{lim}} = 30 \text{ mag}$, $\sim 10\%$ of observable SNe locate at $z \geq 3$. Since the reachable redshift increases dramatically if $m_{\text{lim}} \geq 26-30 \text{ mag}$ is feasible, the next-generation telescopes/instruments will considerably enhance the reachable redshift. The reachable redshift is almost independent of the uncertainties involved in the host galaxy extinction and SFH. Therefore, the shock breakout is the most appropriate phenomenon to aim at for the detection of high-$z$ CCSNe. The first detection of normal CCSNe at $z > 1$ can certainly be achieved by the observation of shock breakout in SNe II-P. The direct observation of normal CCSNe at $z > 1$ will shed light on their nature and cosmic evolution histories, most of which are currently derived from galaxy studies that might be biased by brightness of galaxies.

Future/ongoing wide and/or deep surveys, e.g., the Palomar Transient Factory (PTF; Law et al. 2009; Rau et al. 2009), the Lick Observatory Supernova Search (LOSS; Leaman et al. 2011), the Catalina Real-Time Transient Survey (CRTS; Drake et al. 2009), the Kiso/Kiso Wide Field Camera (KWFC),25 Skymapper,26 the Dark Energy Survey (DES; Bernstein et al. 2009), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Kaiser et al. 2002; Kaiser 2004), the Subaru/Hyper Suprime-Cam (HSC; Miyazaki et al. 2006), and the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008), will find a large number of shock breakouts. We simulate realistic survey strategies and show that a wider and shallower survey leads to a higher observable SN rate with a given survey power but misses the higher-$z$ events. And the observable SN rate for short integration is suppressed by the overhead. Although the survey parameters should be customized to observation purposes and the telescope/instrument, we conclude that the most essential observation is the multicolor photometry with short intervals less than 1 day and that the observation over $\geq 2$ continuous nights is favorable.

We also establish the ways to identify shock breakouts and to constrain the SN properties from those observations. The LC, color, position, and past or wide frequency-coverage observations excellently distinguish shock breakout from the variable stars, SNe, GRBs, and QSOs. In particular, the blue color of shock breakout is the most important information to identify shock breakout. Shock breakout in an SN II-P with larger $R_{\text{preSN}}$ evolves more slowly and has a more luminous peak in the optical bandpass. The two observational quantities, timescale and color evolution, can reasonably determine the SN properties, $R_{\text{preSN}}$ ($M_{\text{MS}}$) and $E$, being independent of the host galaxy extinction. When numerous shock breakouts are detected, the IMF in the high-$z$ universe will be constrained by the shock breakouts. Furthermore, if the SN properties can be determined only from the timescale and color variation with time, the other two observational quantities, peak magnitude and absolute color, can determine the host galaxy extinction. Combining the observations of the host galaxies, the relation between the host galaxy and its stellar contents might be constrained.

Shock breakout enables an untargeted CCSN survey at unprecedentedly high redshift, which can provide large uniform CCSN samples with the comparable redshift range with GRBs. This would allow us to clarify the relation between GRBs and star formation and thus the GRB progenitors. GRBs are hosted in blue, faint, and/or low-Z galaxies (Le Floc’h et al. 2003; Kewley et al. 2007; Levesque et al. 2010) and thus have been suggested to require low-Z progenitors. On the other hand, Kocevski & West (2010) and Mannucci et al. (2011) recently suggest that the GRB hosts follow a tight correlation among stellar mass, metallicity, and SFR of field galaxies and that the characteristics of GRB hosts can be explained only by the large SFR in low-Z galaxies. If the latter is correct, the host galaxies of CCSN should share the same properties as the GRB hosts because the lifetimes of GRB and CCSN progenitors are similar.27 However, it is suggested that the GRB hosts are fainter and more irregular at $z < 1.2$ and have lower-Z at $z < 0.3$ than the CCSN hosts (Fruchter et al. 2006; Modjaz et al. 2008), although there is room for improvement, e.g., the statistics and uniformity. Hence, the large CCSN sample of the same quality as GRBs, especially for survey method and redshift range, could give unique information on the environment of GRBs. The comparison between CCSN and GRB hosts at $z > 1$ can provide an essential clue for understanding the issue. It will probe whether an SFH estimate with GRBs, which is extendible to $z \geq 8$, are biased or not.

Aspherical shock breakout in a cocoon or a jet is suggested for Type Ic SN 2006aj/GRB 060218 (e.g., Soderberg et al. 2006; Campana et al. 2006; Waxman et al. 2007; Ghisellini et al. 2007) and Type Ib SN 2008D/XRF 080109 (e.g., Soderberg et al. 2008; Mazzali et al. 2008). The asphericity stems from the compactness of the progenitor which leads to relativistic outflow at the tip of shockwave. Therefore, in order to precisely deal with aspherical shock breakout, a multidimensional relativistic radiation hydrodynamics calculation is required but has not been attained so far. On the other hand, polarization observations demonstrate that SNe II-P have a spherical structure at the plateau phase even with an aspherical inner core (e.g., Leonard et al. 2006; Wang & Wheeler 2008). This is because the progenitor of an SN II-P has a thick H envelope diluting the asphericity. Therefore, assuming the spherical symmetry is reasonable for SNe II-P and the results are applicable for all SNe II-P.

Recently Smartt et al. (2009) suggests that there is a maximum mass for the progenitor that can be SNe II-P ($M_{\text{MS}} \lesssim 16.5 \pm 1.5 \text{ M}_\odot$).28 This suggestion cautions the existence of a massive SNe II-P with $M_{\text{MS}} > 20 \text{ M}_\odot$. However, the constraints are limited only to SNe II-P having occurred in the nearby universe, in which individual stars can be resolved. It is not investigated whether such a low maximum mass for SNe II-P exists in the high-$z$ universe or at low-Z environments. Also, the reason why the stars with $M_{\text{MS}} > 20 \text{ M}_\odot$ cannot be SNe II-P is under debate. Some studies suggested that such a massive star forms a black hole directly (e.g., Smartt 2009) or explodes as other kinds of SNe due to strong mass loss and/or rotation (e.g., Smartt et al. 2009; Yoon & Cantillo 2010; S. Ekström et al. 2011).

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25 http://www.ioa.s.u-tokyo.ac.jp/kisohp/top_e.html
26 http://www.mso.anu.edu.au/skymapper/

27 For example, the lifetimes of stars with $M_{\text{MS}} \geq 40 \text{ M}_\odot$, a putative GRB progenitor, and $M_{\text{MS}} \geq 10 \text{ M}_\odot$, a putative CCSN progenitor, are less than 5 Myr and 20 Myr, respectively (Schaller et al. 1992). In order to make a difference between GRB and CCSN hosts, the star formation in the host galaxies should cease 5–20 Myr ago or start $\leq 5$ Myr ago. Although it is still under debate how short duration of star formation activity is allowed (e.g., Mas-Hesse & Kunth 1999; McQuinn et al. 2010), such short timescales are comparable with the age spreads of OB associations and the lifetimes of giant molecular clouds (McKee & Ostriker 2007, and references therein).
28 Dessart et al. (2010) also suggests that this constraint is consistent with the nebular observations of SNe II-P.
in preparation). However, both scenarios are not conclusive because some of stars with $M_{\text{MS}} \geq 25 M_\odot$ explode as energetic Type Ic SNe with $E_{51} \geq 10$ (e.g., Iwamoto et al. 1998), which is enough to explode a massive star even with a thick H envelope, and because the mass loss from a massive star is difficult to predict theoretically (e.g., Vink 2008 for review). Furthermore, a fast rotating star that can explain the low maximum mass has a larger presupernova radius at a given mass than a non-rotating star if the H envelope remains (C. Georgy et al. 2011, private communication). This could moderate the reduction of the observable SN rate. The observational properties of shock breakout can constrain the properties of SNe II-P and their progenitors at high redshift. The redshift-dependent number count and properties of shock breakouts can be used to judge when the maximum mass for SNe II-P is established and could give a clue to the origin of the maximum mass for SNe II-P.

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