ILLUMINATING THE PRIMEVAL UNIVERSE WITH TYPE IIn SNSupernovae

Daniel J. Whalen1,11, Wesley Even2, C. C. Lovekin3, Chris L. Fryer4, Massimo Stiavelli5, P. W. A. Roming6,7, Jeff Cooke8, T. A. Pritchard7, Daniel E. Holz9, and Cynthia Knight3,10

1 Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA
2 XTD-6, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
3 T-2, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
4 CCS-2, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
5 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
6 Space Science & Engineering Division, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA
7 Department of Astronomy & Astrophysics, Penn State University, 525 Davey Lab, University Park, PA 16802, USA
8 Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, H30, Hawthorn, Victoria 3122, Australia
9 Enrico Fermi Institute, Department of Physics, and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
10 Department of Physics and Astronomy, Brigham Young University, Provo, UT 84602, USA

ABSTRACT

The detection of Population III (Pop III) supernovae (SNe) could directly probe the primordial initial mass function for the first time, unveiling the properties of the first galaxies, early chemical enrichment and reionization, and the seeds of supermassive black holes. Growing evidence that some Pop III stars were less massive than $100 \ M_\odot$ may complicate prospects for their detection, because even though they would have been more plentiful, they would have died as core-collapse SNe, with far less luminosity than pair-instability explosions. This picture greatly improves if the SN shock collides with a dense circumstellar shell ejected during a prior violent luminous blue variable type eruption. Such collisions can turn even dim SNe into extremely bright ones whose luminosities can rival those of pair-instability SNe. We present simulations of Pop III Type IIn SN light curves and spectra performed with the Los Alamos RAGE and SPECTRUM codes. Taking into account Ly$\alpha$ absorption in the early universe and cosmological redshifting, we find that $40 \ M_\odot$ Pop III Type IIn SNe will be visible out to $z \sim 20$ with the James Webb Space Telescope and out to $z \sim 7$ with WFIRST. Thus, even low mass Pop III SNe can be used to probe the primeval universe.

Key words: early universe – galaxies: high-redshift – hydrodynamics – radiative transfer – stars: early-type – supernovae: general

Online-only material: color figures

1. INTRODUCTION

The first stars in the universe are thought to form in $10^2$–$10^4 \ M_\odot$ cosmological halos at $z \sim 20$–30. Unfortunately, because these stars lie at the edge of the observable universe there are no observational constraints on their properties. The original numerical simulations of primordial, or Population III (Pop III), star formation suggest that they are very massive, $100$–$500 \ M_\odot$, and that they form in isolation, one per halo (Bromm et al. 1999, 2002; Abel et al. 2000, 2002; Nakamura & Umemura 2001; O’Shea & Norman 2007, 2008; Wise & Abel 2007; Yoshida et al. 2008). Newer calculations have since found that some Pop III stars may form in binaries (Turk et al. 2009) or even small swarms of $20$–$40 \ M_\odot$ stars (Stacy et al. 2010; Clark et al. 2011; Smith et al. 2011; Greif et al. 2011, 2012). Simulations of UV breakout from primordial star-forming disks suggest that ionizing feedback in some cases may limit the masses of the first stars to $20$–$50 \ M_\odot$ (Hosokawa et al. 2011, 2012; Stacy et al. 2012a; but see also Omukai & Palla 2001, 2003; Omukai & Inutsuka 2002; Tan & McKee 2004; McKee & Tan 2008). However, all these estimates must be regarded as very preliminary, since no simulation has evolved a newly formed Pop III protostellar disk all the way to the end of the life of one of its stars with realistic physics (for recent reviews, see Glover 2013; Whalen 2012). Furthermore, the impact of turbulence (Latif et al. 2013), magnetic fields due to the small scale turbulent dynamo (Schober et al. 2012), and radiation transport on the evolution and stability of the disk are not well understood. There have been attempts to constrain the Pop III initial mass function (IMF) by modeling the nucleosynthetic imprint of primordial supernovae (SNe) on later generations of stars. This imprint is now sought in the fossil abundance record, the pattern of chemical elements found in ancient, dim metal-poor stars now being surveyed in the Galactic halo (e.g., Cayrel et al. 2004; Beers & Christlieb 2005; Frebel et al. 2005; Lai et al. 2008; Caffau et al. 2012). Recent simulations indicate that $15$–$40 \ M_\odot$ Pop III core-collapse (CC) SNe may have contributed significantly to early chemical enrichment, further corroborating the existence of lower-mass Pop III stars (Joggerst et al. 2010). Some have taken the absence of the distinctive odd–even nucleosynthetic pattern of pair-instability (PI) SNe (Heger & Woosley 2002) in extremely metal-poor stars to imply that there were no very massive Pop III stars. However, evidence of the odd–even effect has now been found in high-redshift damped Ly$\alpha$ absorbers (Cooke et al. 2011) and perhaps in a new sample of stars from the Sloan Digital Sky Survey (SDSS; Ren et al. 2012). It is also now known that Pop III PI SNe could easily have enriched later stars to metallicities above those targeted by surveys to date (Karlsson et al. 2008; Joggerst & Whalen 2011; Chen et al. 2011). Much remains to be understood about how metals from the first stars are taken up into later generations by cosmological flows (e.g., Greif et al. 2007; Chiaki et al. 2013; Ritter et al. 2012). Nevertheless, it is clear that low-mass Pop III stars may have been common in the early universe, with profound consequences for the character
of primitive galaxies (Johnson et al. 2008, 2009; Greif et al. 2008, 2010; Jeon et al. 2012; Pawlik et al. 2011, 2013; Wise et al. 2012), early reionization (Whalen et al. 2004; Kitayama & Yoshida 2005; Alvarez et al. 2006; Abel et al. 2007; Wise & Abel 2008) and chemical enrichment (Mackey et al. 2003; Smith & Sigurdsson 2007; Smith et al. 2009), and the origins of supermassive black holes (Bromm & Loeb 2003; Johnson & Bromm 2007; Djorgovski et al. 2008; Milosavljević et al. 2009; Alvarez et al. 2009; Lippai et al. 2009; Tanaka & Haiman 2009; Li 2011; Park & Ricotti 2011, 2012a, 2012b; Johnson et al. 2012a, 2012b; Whalen & Fryer 2012; Agarwal et al. 2012).

The best prospects for determining the masses of Pop III stars in the near term lie in detecting their SNe (Bromm et al. 2003; Kitayama & Yoshida 2005; Whalen et al. 2008c; Vasiliev et al. 2012). Even though they are extremely luminous (Schaerer 2002), individual primordial stars are still too dim to be found by the James Webb Space Telescope (JWST; Gardner et al. 2006) or 30 m class telescopes (although in principle their H Ii regions could be detected via strong gravitational lensing; Rydberg et al. 2013). Pop III SNe can be 100,000 times brighter than their progenitors or the host galaxies in which they reside, and their masses can be inferred from their luminosity profiles. The main obstacle to their detection is Lyman absorption by neutral hydrogen prior to the era of reionization, which absorbs or scatters most photons from these ancient explosions out of our line of sight. Pop III SNe must emit enough luminosity below the Lyman limit to be observed in the near-infrared (NIR) locally. Whalen et al. (2012a, 2012b, 2013) recently found that JWST will detect Pop III PI SNe at any epoch and the Wide-Field Infrared Survey Telescope (WFIRST) and Wide-field Imaging Surveyor for High-Redshift (WHISH) will find them out to \( z \approx 15-20 \) in all-sky NIR surveys (see Scannapieco et al. 2005; Kasen et al. 2011; Pan et al. 2012a, 2012b; Hummel et al. 2012; Dessart et al. 2013, for past studies of PI SNe and their detection). Their extreme brightnesses make PI SNe ideal probes of the earliest stellar populations (see Gal-Yam et al. 2009; Young et al. 2010, on the detection of the SN 2007bi, a PI SN candidate in the local universe).

Pop III CC SNe may be more plentiful at high redshifts but they are more difficult to detect because of their lower luminosities. Whalen et al. (2012c) calculate detection limits of \( z \approx 10-15 \) for 15–40 \( M_\odot \) Pop III CC SNe for JWST for explosion energies of 1–2 \( \times 10^{51} \) erg, so they can be found in primitive galaxies but not in the first star-forming halos. CC explosions also cannot be used to differentiate between primordial and Pop II progenitors in protogalaxies because their central engines are not very sensitive to metallicity (Chieffi & Limongi 2004; Woosley & Heger 2007). Such events can therefore trace star formation rates in the first galaxies but are not ideal probes of the primordial IMF.

However, some CC SNe, Type IIn SNe, have recently been discovered with luminosities that rival those of far more powerful explosions. SN 2006tf and SN 2006gy, whose bolometric luminosities exceed \( 10^{44} \) erg s\(^{-1} \) and are on par with those computed for Pop III PI SNe (see, e.g., Gal-Yam 2012), have now been observationally and theoretically connected to the collision of SN ejecta with a dense circumstellar shell ejected by a violent luminous blue variable (LBV) eruption a few years prior to the death of the star (Smith & McCray 2007; Gal-Yam et al. 2007; Gal-Yam & Leonard 2009; van Marle et al. 2010; Chevalier & Irwin 2011). The shell is thought to be opaque because only photons from the collision are observed, not those from shock breakout from the surface of the star. Type IIn SNe likely occur at high redshifts because 15–40 \( M_\odot \) Pop III stars that do not have much convective mixing over their lifetimes are known to die as compact blue giants (Scannapieco et al. 2005; Joggerst et al. 2010; see also Ekström et al. 2008; Stacy et al. 2011, 2012b; Yoon et al. 2012 on the effect of rotation and magnetic fields on the evolution of Pop III stars). They may be observable at redshifts above those at which normal luminosity CC SNe can be detected because the shell becomes extremely luminous in UV when the ejecta crashes into it (Moriya et al. 2010, 2013; Tanaka et al. 2012; see also Tomimaga et al. 2011).

We have modeled Pop III Type IIn SNe and their light curves and spectra with the Los Alamos RAGE and SPECTRUM codes in order to calculate their detection limits in redshift and their NIR signatures. In Section 2 we describe our explosion and shell models and how they are evolved in RAGE. Blast profiles, light curves, and spectra are examined in Section 3, and in Section 4 we compare light curves from our models with those of Type IIn SN candidates observed in the local universe. In Section 5 we calculate NIR light curves for Pop III Type IIn at high \( z \) and determine their detection limits as a function of redshift. In Section 6 we conclude.

2. NUMERICAL MODELS

We take the z40G SN from Whalen et al. (2012c; hereafter WET12) to be our fiducial explosion model. It is a zero-metallicity, \( 40 M_\odot \), \( 2.4 \times 10^{51} \) erg CC SN. This progenitor was evolved from the beginning of the main sequence up to the point of explosion in the Kepler code (Weaver et al. 1978; Woosley et al. 2002), at which point the SN was artificially triggered and followed until the end of nuclear burning. Profiles for the blast, which at this point was still deep in the star, were then mapped onto a two-dimensional grid in the CASTRO adaptive mesh refinement (AMR) code (Almgren et al. 2010) and evolved until just before shock breakout to capture mixing inside the star due to Rayleigh–Taylor instabilities. We begin this study by spherically averaging the final CASTRO density, energy, velocity, and mass fractions and mapping them onto a one-dimensional spherical AMR grid in RAGE together with the surrounding star, its wind and a variety of dense shells.

We adopted z40G, a red supergiant progenitor rather than a blue compact giant star like those thought to be the origin of LBV outbursts, because its larger surface area gives an upper limit to the luminosity from shock breakout and hence the number of photons that initially escape through the shell. The dynamics of the collision with the shell is not sensitive to the structure of the star. Had we instead used the u40G explosion a greater fraction of the breakout transient would have gotten through the shell because more of it would have been X-rays (shocks breaking out of compact stars are hotter than those breaking free from red giants for a given explosion energy). On the other hand, blue stars have smaller surface areas and this compensates for higher shock temperatures in the flux. None of these issues impact detection limits because the breakout pulse is completely absorbed by the neutral intergalactic medium (IGM) at high redshift.

2.1. RAGE

RAGE (Radiation Adaptive Grid Eulerian; Gittings et al. 2008) is a multidimensional AMR radiation hydrodynamics code developed at Los Alamos National Laboratory (LANL). It couples second order conservative Godunov hydrodynamics to gray or multigroup flux-limited diffusion (FLD) to model...
strongly radiating flows. Our RAGE root grid has 200,000 zones with a resolution of \(4.0 \times 10^{10}\) cm and reflecting and outflow conditions on the inner and outer boundaries, respectively. Our choice of mesh ensures that all important features of the shock, the star, and the shell are resolved by at least 10 zones and that 5000 zones are allocated from the center of the grid to the outer edge of the shock at setup. As in WET12, we allow up to five levels of refinement so each feature can be further resolved by up to 320 additional zones if necessary, and we again periodically resample the explosion onto larger grids to accommodate its expansion and speed up the calculation. All physics in the WET12 models are used here: multi-species advection, gray FLD radiation transport with Los Alamos OPLIB atomic opacities\(^\text{12}\) (Magee et al. 1995), two-temperature physics, and energy deposition due to radioactive decay of \(^{56}\text{Ni}\).

We evolve the explosion through breakout from the star, collision with and propagation through the shell, and expansion into the IGM out to 500 days. When we post-process dumps from RAGE with SPECTRUM to obtain light curves, we sample shock breakout from the star with 50 spectra at evenly spaced times that bracket the thermal transient and 200 spectra at logarithmically spaced times out to 500 days. Computing spectra in this manner allows us to model with detailed opacities how the shell attenuates both the initial breakout pulse and the flash from its own lower layers when the ejecta collides with it.

### 2.2. SPECTRUM

RAGE profiles are imported into the LANL SPECTRUM code (Frey et al. 2013) in order to calculate spectra with monochromatic OPLIB atomic opacities that capture detailed emission and absorption line structure. As explained in Frey et al. (2013), densities, velocities, and gas and radiation energy densities from the most refined levels in the RAGE AMR hierarchy are first extracted and reordered by radius into separate data files. These profiles are then mapped onto a two-dimensional grid in radius and \(\mu = \cos \theta\) in SPECTRUM. The spectrum calculation is done with 5200 radial bins and 160 angular bins, the same number as in WET12 but with a slightly modified gridding strategy. The simulation volume is divided into three regions: inside the \(r = 20\) surface, between the \(r = 20\) surface and the radiation front, and beyond the radiation front. The position of the radiation front is taken to be the outermost cell with a temperature above 0.0292 eV, approximately three times the background temperature of 0.01 eV (136 K). The radius of the \(r = 20\) surface is calculated from the outer edge of the grid assuming \(\kappa = 0.2\) cm\(^2\) g\(^{-1}\), that due to electron scattering in gas at primordial composition, 76% H and 24% He by mass. To avoid allocating too many zones to the cold dense shell and under-resolving the shock prior to its impact with the shell, the \(20\) surface calculation excludes the density of the shell before the collision. If a zone in the shell has not received additional momentum from the shock then the density in that cell is replaced with what the wind density would be at that location. This allows SPECTRUM to adequately resolve the photosphere of the ejector prior to its collision with the shell and then the shell itself when it becomes the dominant source of flux.

### 2.3. Shell Structure

Pop III stars are not normally thought to lose much mass over their lifetimes because there are no line driven winds in their metal-free atmospheres (Kudritzki 2000; Vink et al. 2001; Baraffe et al. 2001; Krtička & Kubát 2006; Ekström et al. 2008). However, these studies do not exclude the possibility of violent pulsational mass loss late in the life of massive primordial stars. For simplicity, we adopt the shell structure used in van Marle et al. (2010), a transient, high-mass flux that interrupts the more diffuse wind blown by the star before and after the ejection. The two winds have the same constant velocity but different uniform mass-loss rates that together create a density profile that is a simple superposition of two winds:

\[
\rho(r) = \begin{cases} \\
\frac{m_w}{4\pi r v_w} & \text{if } r \leq r_1 \text{ and } r \geq r_2 \\
\frac{m_{sh}}{4\pi r v_w} & \text{if } r_1 < r < r_2.
\end{cases}
\]

Here, \(m_w\) and \(m_{sh}\) are the mass-loss rates of the wind and the shell, where

\[
\dot{m}_{sh} = \frac{M_{sh}}{d_{t_{sh}}}
\]

and \(v_w\) is the wind speed. The two radii \(r_1\) and \(r_2\) mark the inner and outer surfaces of the shell,

\[
r_1 = v_w t_{end},
\]

\[
r_2 = v_w (t_{end} + d_{t_{sh}}),
\]

where \(t_{end}\) is the time between the end of the ejection and the SN, and \(d_{t_{sh}}\) is the duration of the ejection. As in van Marle et al. (2010), \(t_{end}\) and \(d_{t_{sh}}\) are 2 yr in all our models and we vary the density of the shells by adjusting \(M_{sh}\). We take the shells to be primordial, 76% H and 26% He by mass fraction. Density profiles for the five shells in our study together with the 40 \(M_\odot\) star are shown in Figure 1, and we summarize the properties of the shells in Table 1.

The aim of our numerical campaign is to explore the observational signatures and detection thresholds of Pop III Type Ibn SNe, not to perform an exhaustive survey of such explosions.
We adopt this type of shell to compare our light curves with those of van Marle et al. (2010) and because it is similar in mass and structure to the shell inferred to exist around η Carinae from observations. Density profiles for actual LBV eruptions are likely more complicated, with fast winds preceding and following much slower outbursts that create multiple shocks and rarefaction zones similar to those found in Mesler et al. (2012). Radiative cooling would also flatten the shell into a colder and denser structure than the ones shown here if dust and metals are present. Type IIn SNe in the local universe will be examined in a forthcoming study.

2.4. Ionization State of the Shell

Before launching our runs in RAGE we performed a separate test to determine whether UV radiation from the star ionizes the shell (see, e.g., Whalen et al. 2004). The ionization state of the shell determines its opacity to the SN before and after its collision with the shell. It may also influence how efficiently the kinetic energy of the ejecta is transformed into radiation upon impact with the shell, and hence its luminosity. Both issues are relevant because the progenitor can be tens of solar masses and therefore a very luminous source of ionizing UV photons, and there is little if any dust in the vicinity of the star to attenuate them.

We use the ZEUS-MP code to determine whether the star ionizes its shell (Whalen & Norman 2006, 2008a, 2008b). ZEUS-MP self-consistently solves hydrodynamics, nonequilibrium H and He chemistry and ionizing UV transport to propagate cosmological ionization fronts. We consider a 250 $M_\odot$ Pop III star in shell A00 from Table 1. The wind and shell are initialized on a one-dimensional spherical mesh with 200 uniform zones and inner and outer boundaries at 1.3 \times 10^{13} m (the surface of the star) and 3.0 \times 10^{15} m (the outer surface of the shell 2 yr after the end of the ejection). We use multifrequency UV transport, with 40 bins uniformly partitioned in energy from 0.255 to 13.6 eV and 80 bins logarithmically spaced from 13.6 to 90 eV. The blackbody spectrum of the star is normalized to ionizing photon emission rates, surface temperatures, and luminosities from Schaefer (2002). The shell is illuminated for 4 yr, the time from the onset of ejection to the SN. This treatment is approximate, given that the shell is initially closer to the star and exposed to higher fluxes just after explosion. Because a 250 $M_\odot$ star is more luminous than a Type IIn progenitor, its ionizing flux is the extreme upper limit that could be reasonably applied to the shell.

We find that the radiation front from the star easily ionizes the wind on timescales of a few hours but is halted by the shell without ionizing even one zone of it. Since the star is incapable of ionizing the least massive shell in our study, we take all the shells in our RAGE models to be neutral. We note that had the shells been ionized, they would fully recombine by the time the explosion reaches them. This is evident from the recombination timescales in the gas,

$$t_{\text{rec}} = \frac{1}{n_e \alpha(T)},$$

where

$$\alpha(T) = 2.59 \times 10^{-13} T_4^{-0.75} \text{cm}^3 \text{s}^{-1}$$

is the case B recombination rate coefficient for hydrogen, $n_e$ is the electron number density, and $T_4$ is the temperature in units of 10^4 K. With densities of 10^9 cm^{-3} in the A00 shell and ionized gas temperatures $T \sim 10,000$ K, $t_{\text{rec}}$ is about an hour.

3. POP III IIn SN LIGHT CURVES AND SPECTRA

We show bolometric light curves for all five explosions in the source frame out to 60 days and 500 days in the left and right panels of Figure 2, respectively, and spectra for shock breakout from the surface of the star in Figure 3. Blast profiles for the A04 explosion are shown in Figures 4–6. The evolution of the SN can be partitioned into three distinct phases: (1) the collision of a radiative precursor with the shell; (2) the collision of the ejecta with the shell and its propagation through the shell; and (3) breakout from the outer surface of the shell and expansion into the surrounding medium.

3.1. The Radiative Precursor

As shown in the left panel of Figure 2, some flux from shock breakout from the surface of the star passes through all five shells. The breakout transient, shown at 5 days in the left panel of Figure 2, is $\sim 5 \times 10^{45}$ erg s^{-1} but is reduced to $10^{43}$ erg s^{-1} by the A00 shell and to $10^{41}$ erg s^{-1} by the A04 shell. This attenuated flux is unlikely to be detected because it is relatively dim and because the shell becomes much brighter later on. As we show in Figure 3, most of the attenuation is due to the absorption of 1000–3000 Å photons. The bolometric luminosity of the shock falls to $10^{42.5}$ erg s^{-1} after about a day and decays slowly thereafter.

The photon pulse blows off the outer layers of the star after breaking free of the shock and drives them across the gap between the star and the shell. This radiative precursor, the feature at $4.0 \times 10^{14}$ cm at 5.6 days in the density and velocity profiles in Figure 4, reaches with the inner surface of the shell at 9 days, well before the ejecta. The collision creates a temperature spike at the inner surface of the shell that is manifest as the small bump in luminosity just after the breakout transient in all five shell light curves. After the initial collision, the wispy outermost layers of the star continue to pile up in a thin layer at the inner surface of the shell, forming a reverse shock that reverberates back and forth through the layer. This can be seen in the temperature profile across the layer: the small spike in temperature at $1.3 \times 10^{15}$ cm, the upper surface of the layer, at 9.0 days rebounds to $9.0 \times 10^{14}$ cm, the lower surface, by 10.9 days. Slightly fewer high-energy photons get through the shell at 10.9 days than 9 days because the reverse shock is at the bottom of the thin layer and more of its radiation is absorbed.

The reverberation of the shock back and forth in this layer causes the flickering in the light curve from 8–32 days. The luminosities are relatively steady over these times because the thin layer is trapped at the inner surface of the shell. However, luminosities for less massive shells are higher because they allow more radiation to pass. The ripples in the A02–A04 light curves are absent from the A00 and A01 light curves for two reasons. First, as we discuss in greater detail below, the ejecta

| Table 1  | Pop III Circumstellar Shell Models |
|---------|---------------------------------|
| Model   | $M_{\text{sh}}$ ($M_\odot$) | $m_{\text{sh}}$ (M$_\odot$ yr$^{-1}$) | $v_{\text{sh}}$ (km s$^{-1}$) |
| A00     | 0.1                            | $10^{-4}$                       | 200                           |
| A01     | 1                              | $10^{-4}$                       | 200                           |
| A02     | 6                              | $10^{-4}$                       | 200                           |
| A03     | 10                             | $10^{-4}$                       | 200                           |
| A04     | 20                             | $10^{-4}$                       | 200                           |

The Astrophysical Journal, 768:195 (15pp), 2013 May 10

Whalen et al.
Figure 2. Bolometric luminosities for all five Type IIn explosions together with the z40G explosion. Left panel: out to 60 days. Right panel: out to 500 days. Shock breakout from the star itself appears as the luminosity spike at 4.5 days, the collision of the radiative precursor with the inner surface of the shell is visible as the small uptick in luminosity at 9 days, and the collision of the ejecta with the shell causes the jump in luminosity at 30–40 days. Breakout of ejecta from the outer surface of the shell is visible as the surge in bolometric luminosity at 60–125 days on the right. (A color version of this figure is available in the online journal.)

never overtakes the inner surface of the A00 shell because its radiation displaces the low-mass shell outward. Second, the radiation front propagates to greater distances through the shell because of its lower density, so there is a larger separation between the front and the $\tau = 20$ surface. As a result, the SPECTRUM code may not resolve the radiating region of the flow and capture small-amplitude fluctuations in luminosity in diffuse shells as well as in more massive shells. In the A02–A04 shells the radiation front and the $\tau = 20$ surface are much closer together and the radiating region is better resolved.

3.2. Collision with the Shell

We show the ejecta just before and after its collision with the shell at 27 days and 49.2 days in Figure 5. When it reaches the inner surface, the ejecta drives a strong shock into the shell, heating it to $\sim 7.5$ eV. The shock drives the inner surface outward, piling it up into the density spike visible at $1.5 \times 10^{15}$ cm at 49.2 days. This 7.5 eV spike is the source of the jump in luminosity at 32 days in the left panel of Figure 2. The magnitude of the jump depends on the density of the shell, with diffuse shells allowing more radiation to pass through them. The light curves appear to plateau from 32–60 days, but the luminosity rapidly rises as the shock propagates through the shell and there is less gas between the shock and the outer surface of the shell to absorb or scatter the photons, as we show at 32–100 days in the right panel of Figure 2. The rise is most pronounced in the densest shells because they initially attenuate the most radiation.

As the ejecta plows up the shell a reverse shock forms and detaches from the forward shock, backstepping into the interior in the frame of the flow. The reverse shock can be seen at $2.0 \times 10^{15}$ cm in the density and temperature profiles at 93.5 days. As it recedes from the forward shock, the reverse shock loses pressure support because of radiative cooling by H and He lines in the shocked gas and it retreats back toward the forward shock. However, as the forward shock continues to plow up the shell the reverse shock is again driven back into the interior. The cyclical heating and cooling of post-shock gas associated with the oscillation of the reverse shock causes the ripples in the luminosities from 32–100 days in the A02–A04 light curves. The period of oscillation is governed by cooling rates in the gas (Imamura et al. 1984) and is independent of shell mass, but the amplitude of oscillation is somewhat correlated with shell density (see also Section 4.1 of Anninos et al. 1997).

Figure 3. Spectra at shock breakout from the surface of the star (4.5 days) for all five Type IIn explosions. The absorption features at 1000–3000 Å due to the shell cause the drop in bolometric luminosity at 4.5 days. (A color version of this figure is available in the online journal.)
3.3. Breakout from the Shell

The shock breaks free from the outer surface of the shell at times that depend on the mass of the shell, from \( \sim 45 \) days in \( \text{A01} \) to \( \sim 120 \) days in \( \text{A04} \). As shown in the velocity profiles at 120 and 139 days in Figure 6, the shock abruptly accelerates in the sharp density drop just outside the shell. Photons from the shock also stream into the surrounding medium, creating the second jump in luminosity to \( \sim 10^{43.5} \text{ erg s}^{-1} \) that persists for 50–100 days in the right panel of Figure 2. Because the peaks coincide with shock breakout, they also occur at 45–120 days. Diffuse shells result in broader peaks because they allow photons to escape from greater depths and earlier times in the shell. As we show at 120 days in the temperature profile, low-energy photons begin to leak through the shell well before shock breakout at 139 days.

Such features are also found in \( \text{Ly} \alpha \) emission by primordial SN remnants at later times as they sweep up neutral gas in halos on larger scales (see Figure 11 in Whalen et al. 2008c). The stability of radiative shocks in astrophysical contexts has been well studied (e.g., Chevalier & Imamura 1982). We note that the spectrum becomes harder from 27 to 93.5 days even though the shock cools because there is less absorption by the shell as the shock plows through it.
Radiation from the shock again blows off the outer layers of the shell, creating the density peak at the edge of the radiation front at \(4.0 \times 10^{15}\) cm at 139 days. These photons ionize the envelope beyond the shell, allowing more energetic photons with \(\lambda > 100\) Å to pass through, as shown in the spectrum at 154 days. As the shock expands it cools, and the ambient density falls. From 154 to 500 days both of these effects are evident in the spectrum. The peak of the spectrum shifts to longer wavelengths but more and more high energy photons escape into the IGM. At 500 days the spectrum is nearly blackbody when its cutoff at high energies has fallen below the Lyman limit and ambient densities are very low. From 250–500 days all five light curves gradually dim as the shock expands and cools.

3.4. A00

The A00 explosion evolves somewhat differently because its shell is so diffuse. The radiative precursor crosses the gap between the ejecta and the shell in \(\sim 9\) days, but radiation from the ejecta has already permeated and warmed the shell. The precursor piles up in a thin layer at the inner surface of the shell as in the other cases, but as the ejecta approaches this surface the gap is never fully closed. Radiation in the gap both displaces the inner surface outward and drives a reverse shock into the ejecta, as we show at 20.3, 40.9, and 59.3 days in Figure 7. The ejecta drives the inner surface forward while remaining separated from it by radiation forces. As shown at
59.3 days, there is still a gap between the ejecta and the shell, and radiation from the shock has leaked through the shell. By this time the outer edge of the shell has also begun to be displaced outward and it is quickly accelerated to the same velocity as the ejecta.

This sequence of flow has several consequences for the A00 light curve. First, as seen in Figure 2, the luminosity from 8–32 days is higher because more radiation from the collision of the precursor with the shell gets through the shell. Next, because the ejecta following the precursor is prevented from colliding with the shell by radiation in the gap between them, the rise in luminosity as the ejecta approaches the shell is very gradual, without the well-defined jump at ~32 days in the A02–A04 light curves. Besides being more transparent to radiation, the A00 shell is also swept up more quickly than the others. The shock that is driven by the radiative gap reaches the outer surface of the shell at 60 days, when its luminosity peaks. From 32–60 days the shock is far less luminous than in more massive shells because the A00 shell is being rapidly accelerated to the velocity of the ejecta. Consequently, the kinetic energy of the ejecta is not efficiently converted into thermal energy, and the shock is weaker and dimmer while it is in the shell. Finally, the luminosity jump at breakout in the other shells is absent in the A00 light curve because the ejecta never actually passes through the shell.
SNe in low-mass shells are much dimmer than those in shells above $1\ M_\odot$.

The A00 light curve rebrightens between 110 and 220 days because the photosphere sinks into the ejecta and encounters layers of higher density and temperature, so the broad peak at 220 days is due purely to optical depth. A similar feature is visible at 240 days in the A01 light curve. The evolution of the A01 explosion is intermediate to that of A00 and the others. Its luminosity gradually rises from 8–32 days because radiation from the impact of the outer layers of the star with the shell gets through the shell and intensifies as gas piles up at the inner surface. Next, because a radiatively supported gap again softens the collision of the ejecta with the shell, the rise in luminosity upon impact is again more gradual than with more massive shells but more prominent than in the A00 light curve. For shell masses greater than $1\ M_\odot$, breakout luminosities from the shell are $10^{43.5}$–$10^{43.8}$ erg s$^{-1}$.

3.5. Earlier Simulations

Not surprisingly, radiation transport leads to important qualitative differences between our light curves and those of van Marle et al. (2010), even though we use the same shells in our models. van Marle et al. (2010) equate energy losses due to optically thin radiative cooling in the gas with the bolometric luminosity of the SN remnant and hence do not account for absorption by the optically thick shell. These losses
are greatest when the gas is most strongly shocked, when the ejecta strikes the inner surface of the shell. Consequently, the van Marle et al. (2010) light curves peak upon initial collision when in reality most of these photons are absorbed in the lower layers of the shell (compare their Figure 11 at 25 days with the right panel of Figure 2 at 32 days). On the other hand, because collisional gas cooling scales as \( \rho^2 \) in van Marle et al. (2010), their bolometric luminosities plummet when the shock breaks out into the low-density medium beyond the shell (compare their Figure 11 at 60–100 days with Figure 2 at 50–100 days). As shown in Figure 2, the light curve actually peaks at this point because photons previously trapped in the shock are free to stream into the IGM, and as the shock pushes down the density gradient it heats and radiates additional energy. When the SN collides with the shell our light curves are therefore initially dim and later peak upon breakout from the shell, while the converse is true of the van Marle et al. (2010) light curves. We note that our shock propagates through the shells in about the same times as in van Marle et al. (2010).

Interestingly, both approaches yield similar widths for the light curves at peak luminosity. The width of the peak is closely tied to the propagation time through the shell in van Marle et al. (2010) but is largely a function of the subsequent expansion and cooling of the remnant in our models. Since shock temperatures peak at only \( \sim 8 \) eV upon impact with the shell, we do not find any X-ray emission after breakout from the surface of the star but the SN is bluer out to much later times than in z40G by itself. This property makes Type II In SNe ideal candidates for high redshift detection. We note that some of the light curves in Figures 10 and 11 of van Marle et al. (2010) exhibit the same flickering as in ours, probably also because of oscillations of reverse shocks due to radiative cooling. They are especially prominent as the shock plows through the A00 shell in Figure 11, when a reverse shock is likely to detach from the forward shock. Finally, because van Marle et al. (2010) model the SN profile as a free expansion and do not consider breakout from the star, none of the features from 8–32 days in our light curves are present in theirs.

We note that while the shock never reaches temperatures at which it would emit X-rays in our models, this in part is due to the fact that we assume that ions and electrons are closely coupled. Because the electrons and the photons are also closely coupled, the ions rapidly lose energy to the radiation field. Because \( e_{\text{gas}} = C_T T \) and \( e_{\text{rad}} = a T^4 \), large transfers of energy into the radiation field do not result in large changes in its temperature, so the radiation and matter temperatures remain modest and there are only mild deviations between them in our simulations. In reality, the ions may not couple efficiently to electrons when the shock collides with the inner surface of the shell or breaks free from its outer surface and the shock may heat them to much higher temperatures than the radiation temperature. Under these circumstances the ions may drive a small fraction of the electrons out of equilibrium with the radiation field and cause them to emit X-rays in real SN remnants.

Comparison of the more recent light curves of Moriya et al. (2013) with ours is more problematic, in part because they assume much higher explosion energies (\( 10–50 \times 10^{51} \) erg, rivaling those of PII SNe) and because they adopt a different structure for the shell. As a result, their peak luminosities are 5–10 times higher than ours but have similar widths. Our bolometric light curves are otherwise qualitatively similar to theirs (compare their Figure 5 to the left panel of Figure 2). Their large explosion energies are necessary to achieve the peak bolometric luminosities of SN 2006gy (Smith et al. 2007, 2008b) and they are not normal CC events.

4. TYPE II In SNe IN THE LOCAL UNIVERSE

We now compare bolometric luminosities for our five explosions to those of Type II In SNe discovered in the local universe: SN2006gy (Smith et al. 2007, 2008b), SN2006tf (Smith et al. 2008a), SN2007pk (Pritchard et al. 2012), SN2008am (Chatzopoulos et al. 2011), SN2010al (Cooke et al. 2010), SN2010jp (Smith et al. 2012), and SN2011ht (Roming et al. 2012; Humphreys et al. 2012). SN2006gy and SN2006tf are the most luminous explosions in this class, while the others exhibit more typical peak luminosities. We group luminosities for A00 and A01 with those of normal Type II In SNe in the right panel of Figure 8 (see Kiewe et al. 2012, for additional examples of Type II In SN light curves) and light curves for A02, A03, and A04 with those for the superluminous SN2006gy and SN2006tf in the right panel of Figure 8. The rise of the light curve is evident in SN2006gy and SN2011ht; the other five data sets only show its decline, making it difficult to pinpoint their explosion times. We therefore assign them times that best align them.
with our simulations. The observations of the normal brightness Type IIn SNe either have very few data points (SN2008am) or cover only short periods of time (SN2007pk, SN2010al, and SN2010jp).

The central engines of Type IIn SNe, the CC explosion, do not vary much with metallicity (Chieffi & Limongi 2004; Woosley & Heger 2007; note also Figure 1 of Whalen & Fryer 2012). It is primarily the structure of the shell and its cooling properties that differentiate Pop III Type IIn SNe from those today. Fine-structure cooling by metals flattens shells into colder, thinner and denser structures than do H and He lines. The thickness of the shell governs the width of the main luminosity peak, so Type IIn events today would likely exhibit narrower peaks and sharper declines in bolometric luminosity, as with SN2010jp and SN2010al. On the other hand, inefficient gas cooling keeps the shock hot and bright, with much slower decays in luminosity at later times like those in Figure 8. More realistic treatments of the ejection would impose additional features on both zero-metallicity and enriched shells that are not present in our models. Slow outbursts are usually preceded and followed by much faster winds. The wind in front of the shell detaches from and races ahead of it, creating a rarefaction zone, while the wind behind the shell piles up at its inner surface and forms a hot termination shock (see Mesler et al. 2012). These structures will imprint additional features on the light curves that have not been captured by any simulations to date. Type IIn SNe in more realistic shells in the local universe will be pursued in future simulations.

In spite of these limitations, the A00 and A01 light curves are consistent with those of the five less luminous Type IIn. They fall between A00 and A01, with rates of decline that are similar to those in the simulations. In particular, A01 is an excellent match to SN2007pk. Because SN2011ht was detected during its rise to peak luminosity, is nearly a factor of three brighter than A04, our brightest light curve. As noted earlier, bolometric luminosities rose only slightly as the mass of the shell went from 6 to 20 $M_\odot$, so more massive shells will not yield better agreement with SN2006gy. The dip at the beginning of the SN2006gy light curve may be photons from shock breakout from the surface of the star filtering through the shell, which only happens with less massive shells. Taken together, these two facts suggest that a more powerful SN is needed to explain SN2006gy, not a more massive shell (which is consistent with Moriya et al. 2013). SN2006tf, the other superluminous explosion, is only marginally brighter than A04. Its bolometric luminosities are close to those of A04 at early and late times, but A04 falls more rapidly and then enters a plateau while SN2006tf declines more steadily. As mentioned above, the plateau is likely due to inefficient H and He cooling in the A04 shell and would probably disappear if the gas was enriched with metals. The A04 light curve in van Marle et al. (2010) is in basic agreement with SN2006gy for shell masses of 20–24 $M_\odot$ and wind velocities of 190 km s$^{-1}$.

Our light curves are in general agreement with recent Type IIn SNe, and some observations match our simulations extremely well. Nevertheless, we do not expect exact agreement because we only used one explosion and shell, and varied only the density of the shell. The shells in our models are also somewhat different from those in real explosions. From Figure 2 it is clear that many of the properties of the shell can be extracted from the light curves, so they can be powerful probes of the circumstellar environment of the explosion.

5. z ∼ 2 TYPE IIn SNe

In Figure 9 we compare $r$-band and $i$-band light curves for the A01–A04 runs with those of Type IIn SNe recently discovered at 1.9 < z < 2.4: SN 0224–0457, SN 0224–0426,
Figure 10. NIR light curves for four shell explosions. Upper left panel: \( z = 7 \); upper right panel: \( z = 10 \); lower left panel: \( z = 15 \); lower right panel: \( z = 20 \). The dashed line at AB mag 32 indicates the JWST NIRCam photometry limit. The first peak at \( z = 7 \) and 10 is due to the initial collision with the shell and cannot be seen at \( z > 10 \). The second peak is caused by breakout from the shell and is visible out to \( z \gtrsim 20 \).

SN 1420 + 5252, and SN 2214−1807 (Cooke et al. 2009, 2012) with the Low Resolution Imaging Spectrometer (Oke et al. 1995; Steidel et al. 2004; McCarthy et al. 1998; Rockosi et al. 2010). These SNe reach peak AB magnitudes of 24.5–26 and are visible for 200–250 days in both bands. Our simulated \( r \)-band light curves exhibit two peaks: a brief initial peak lasting no more than 50 days with magnitudes below 28, and a second brighter and longer peak that reaches magnitudes of 27–28 and lasts up to 500 days. The \( i \)-band light curves also exhibit two peaks but the first one is longer and brighter than in the \( r \)-band: 50–150 days with magnitudes of 26.5 to 27.5. In both bands the first peak is due to the collision of the SN ejecta with the inner edge of the shell and the second peak is due to shock breakout from the shell, when its photons are suddenly able to stream freely in the low density wind. The first peak in the \( i \)-band becomes brighter and longer as the shell mass decreases. In Figure 5, the shock reaches temperatures of \( \sim 10 \) eV and becomes quite luminous upon its collision with and initial advance into the shell. However, these photons must filter through the shell, and the number that escape depends strongly on wavelength. As shown in Figure 5, the opacity of the shell imposes a sharp cutoff on the spectrum at \( \sim 3000 \) Å. This explains the prominence of
the first peak in the $i$ band. The photons that are redshifted into the $i$ band from $z = 2.2$ originate from the brightest region of the spectrum just redward of the 3000 Å cutoff. There is little luminosity in the $r$ band because they are blueward of the cutoff and absorbed by the shell.

The first peak in the synthetic $i$-band light curves better matches the observations than the longer and dimmer late time peak that appears in both bands. If these transients are Type IIn events it is likely that the initial collision with the shell is being observed, and breakout from the shell would be seen later if the surveys were extended. We note that at $z = 2.2$ the progenitors would be Pop II stars, not pristine Pop III stars, and the presence of even small amounts of dust or metals in the shell might have large effects on the opacity and further reduce the magnitude of the first peak in the $i$-band. In addition, our simulation suite only explored the effect of changing the mass in simple analytic shells. The light curves also depend on the energy of the SN explosion, the distance from the SN to the shell, and the thickness of the shell. Therefore, it is not surprising that our five models do not exactly match the observational data. Future simulations are planned to explore a larger parameter space for shell collision SNe in the local universe.

6. NIR LIGHT CURVES

We calculate NIR light curves for Pop III Type IIn SNe with the synthetic photometry code described in Su et al. (2011). We redshift each spectrum to the desired $z$ before removing the flux absorbed by intervening neutral hydrogen clouds with the method of Madau (1995). Each spectrum is then dimmed by dust that are not used here. Our algorithm linearly interpolates the least sampled data between the input spectrum and filter curve. It has additional capabilities such as reddening by dust that are not used here.

We show NIR light curves for all five explosions at $z = 7, 10, 15, 20,$ and $30$ in Figures 10 and 11. In each case we plot the NIR signal in the optimum filter for its detection, which in all cases is redward of the Lyman limit at that redshift. At $z = 7$ and 10, two peaks are visible in the A01–A04 explosions, a narrow, brighter peak at 500–1000 days and a dimmer, broader peak at 2000–2500 days. The first is due to shock breakout from the outer surface of the shell. The second occurs as the redshifted spectral peak evolves downward in wavelength through the NIR as the shell later expands and cools. The first peak is present but not visible at higher redshifts. Its luminosity does not change with shell mass, but more diffuse shells have broader peaks because photons from the shock can escape such shells before the shock, with lead times that are inversely proportional to the density of the shell. The first peak appears at earlier times with low-mass shells because the shock breaks free of them sooner. The A00 light curve does not exhibit this peak because there is no breakout from the shell. In contrast, the luminosity of the second peak rises with shell mass but its width is relatively uniform. As expected, this second peak occurs at later times at higher redshifts.

With NIRCam photometry limits of AB magnitude 31–32, JWST will be able to detect all five explosions out to $z = 20$. With proposed NIR detection limits of AB magnitude 26.5–27, WFIRST and WISH will only be able to observe such events out to $z = 7–10$. At $z = 7$ and 10 the first peak is visible for 250–500 days and the second peak is visible for ~1500 days. At $z = 15$ and 20 the second peak can be seen for ~2000 days but is about a magnitude dimmer. The peaks rise as quickly as they fall, with durations that are comparable to likely protogalactic survey times of 1–5 yr. Because the spectrum of the shock becomes softer as it expands and cools, its NIR light curve evolves on much shorter timescales than its redshifted bolometric luminosity. These events will be easily recognizable as transients and distinguished from protogalaxies.

7. CONCLUSION

Luminous Type IIn SNe will probe stellar populations at $z = 10–20$, redshifts that complement those at which normal-luminosity CC and PI SNe can be detected ($z < 15$ and $z \gtrsim 30$, respectively). They will not trace the first generation of stars, those that form at $z \sim 20–30$, but they will be found during the rise of the Lyman–Werner background ($10 < z < 20$) and in the first galaxies at $z \sim 10–15$. The event rate of Type IIn SNe depends in part on what fraction of 20–40 $M_\odot$ Pop III stars die as compact blue giants or shed a common envelope in a binary, and may be low (Wise & Abel 2005; Weinmann & Lilly 2005; O’Shea et al. 2005; Tornatore et al. 2007; Whalen et al. 2008a, 2010; Trenti et al. 2009; Greif et al. 2010; Maio et al. 2011; Hummel et al. 2012; Johnson et al. 2013; Wise et al. 2012). For example, Tanaka et al. (2012) take this rate to be a few tenths of a percent of the total Type II SN rate. However, such estimates may be too conservative for higher redshifts because the Pop III IMF is known to be top heavy and because the evolution of 20–40 $M_\odot$ primordial stars is still not fully understood.

The other challenge to observing such explosions is that they are too dim to be detected beyond $z \gtrsim 7$ in all-sky NIR surveys by WFIRST or WISH, whose wide fields of view would otherwise compensate for the low SN IIn event rate. This picture could change if the CC event is more energetic than the $2.4 \times 10^{51}$ erg explosion considered here. For example, Moriya et al. (2013) find that SN2006gy is best modeled by a $4 \times 10^{52}$ erg hypernova explosion in a 15 $M_\odot$ circumstellar shell. Such events, with or without shells, may be visible in all-sky NIR
campaigns at much higher redshifts and will be the focus of a future paper.

In our models we assume a uniform shell, but in reality it could be clumpy due to a variety of hydrodynamical instabilities. If so, the ejecta would light up the shell unevenly, with brighter emission emanating from denser clumps than from diffuse regions. It is not clear how the total luminosity of the collision would change in such circumstances. However, this scenario would occur less often in the primordial universe than today because there are no metals or dust to radiatively cool and fracture the shell. Clumping could still occur if the medium into which the shell is ejected is not uniform or if the outflow itself is collimated. The former is less likely at high redshifts because the progenitor star usually drives all the gas from the halo in strong ionized flows, leaving behind diffuse uniform media in the vicinity of the star.

Radio emission from these explosions may be visible at 21 cm by Expanded Very Large Array (eVLA), eMerlin, and the Square Kilometer Array (SKA). Meiksin & Whalen (2013) found that synchrotron emission from CC SNe at \( z = 10–20 \) will be detected by SKA and that more energetic hypernovae at this epoch can be detected by existing facilities. Additional calculations are necessary to determine whether the collision of the ejecta with the shell enhances or quenches its radio emission. Type Ibn SNe are not expected to imprint excess power on the cosmic microwave background (CMB) on small scales because unlike PI SNe, CC SNe are not sufficiently energetic to Comptonize large numbers of CMB photons (Oh et al. 2003; Whalen et al. 2008c).

A small fraction of Pop III CC SNe may proceed as gamma-ray bursts (GRBs; e.g., Bromm & Loeb 2006; Wang et al. 2012), driven either by the collapse of massive rapidly rotating stars (Suwa & Ioka 2011; Nagakura et al. 2012) or binary mergers between 20–50 \( M_\odot \) stars (e.g., Fryer & Woosley 1998; Fryer et al. 1999, 2007; Zhang & Fryer 2001). This is reinforced by the fact that some Pop III stars have been found to form binaries in numerical simulations (Turk et al. 2009). While X-rays from these events could be detected by Swift or next-generation missions such as the Joint Astrophysics Nascent Universe Satellite (JANUS; Mészáros & Rees 2010; Roming 2008; Burrows et al. 2010), it is more likely that their afterglows (Whalen et al. 2008b) will be detected in all-sky radio surveys by the eVLA, eMERLIN, and SKA (de Souza et al. 2011) due to their low event rates. If these events occur in dense circumstellar shells like those in our models, the shells may imprint distinct features on the afterglows (e.g., Mesler et al. 2012). We are now determining the afterglow signatures of Pop III GRBs in a variety of circumburst environments (Mesler et al. 2012; R. A. Mesler et al. 2013, in preparation).

Pop III Type II SNe will completely oustine the primeval galaxies in which they occur because they have comparatively few stars. These stars may reveal the existence of such galaxies when they might not otherwise have been detected by JWST or future 30 m class telescopes such as the Giant Magellan Telescope or the Thirty-Meter Telescope. Together with CC and PI SNe, Pop III shell-collision SNe will trace star formation rates and chemical enrichment in nascent galaxies. These ancient explosions will soon open a new window on the high-redshift universe.

We thank the anonymous referee, whose comments improved the quality of this paper. D.J.W. is grateful for helpful discussions with Lucy Frey and Candace Joggerst and for support from the Bruce and Astrid McWilliams Center for Cosmology at Carnegie Mellon University. M.S thanks Marcia Rieke for making the NIRCam filter curves available and was partially supported by NASA JWST grant NAGS-12458. D.E.H. acknowledges support from the National Science Foundation CAREER grant PHY-1151836. Our work in part is based on observations obtained with MegaPrime and MegaCam, a joint project of CFHT and CEA/IRFU, at the Canada–France–Hawaii Telescope (CFHT), which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. Our work is also based in part on data products produced at Terapix available at the Canadian Astronomy Data Centre as part of the Canada–France–Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS. Work at LANL was performed under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory under Contract No. DE-AC52-06NA25396. All RAGE and SPECTRUM calculations were performed on Institutional Computing (IC) and Yellow network platforms at LANL (Conejo, Lobo, and Yellowrail).

REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2000, ApJ, 540, 39
Abel, T., Bryan, G. L., & Norman, M. L. 2002, Sci, 295, 95
Abel, T., Wise, J. H., & Bryan, G. L. 2007, ApJL, 659, L87
Agarwal, B., Khochfar, S., Johnson, J. L., et al. 2012, MNRAS, 425, 2854
Almgren, A. S., Beckner, V. E., Bell, J. B., et al. 2010, ApJL, 715, 1221
Alvarez, M. A., Bromm, V., & Shapiro, P. R. 2006, ApJL, 639, 621
Alvarez, M. A., Wise, J. H., & Abel, T. 2009, ApJL, 701, L133
Amini, P., Zhang, Y., Abel, T., & Norman, M. L. 1997, New, 2, 209
Baraffe, I., Hege, R., & Woosley, S. E. 2001, ApJ, 550, 890
Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJL, 527, L5
Bromm, V., Coppi, P. S., & Larson, R. B. 2002, ApJL, 564, 23
Bromm, V., & Loeb, A. 2003, ApJ, 596, 34
Bromm, V., & Loeb, A. 2006, ApJL, 642, 382
Bromm, V., Yoshida, N., & Hernquist, L. 2003, ApJL, 596, L135
Burrows, D. N., Roming, P. W. A., Fox, D. B., et al. 2010, Proc. SPIE, 7732, 56
Caffau, E., Bonifacio, P., Prã©vost, P., et al. 2012, A&A, 542, A51
Cayrel, R., Derpã©gne, E., Spite, M., et al. 2004, A&A, 416, 1117
Chatzopoulos, E., Wheeler, J. C., Vinko, J., et al. 2011, ApJL, 729, 143
Chen, K.-J., Heger, A., & Almgren, A. S. 2011, CoPhC, 182, 254
Chevalier, R. A., & Imamura, J. N. 1982, ApJL, 261, 543
Chevalier, R. A., & Irwin, C. M. 2011, ApJL, 729, L6
Chiaki, G., Yoshida, N., & Kitayama, T. 2013, ApJ, 762, 50
Chieffi, A., & Limongi, M. 2004, ApJL, 608, 405
Clark, P. C., Glover, S. C. O., Smith, R. J., et al. 2011, Sci, 331, 1040
Cooke, J., Ellis, R. S., Nugent, P. E., et al. 2010, Atel, 2491, 1
Cooke, J., Sullivan, M., Barton, E. J., et al. 2009, Natur, 460, 237
Cooke, J., Sullivan, M., Gal-Yam, A., et al. 2012, Natur, 491, 228
Cooke, J., Pettini, M., Steidel, C. C., Rudie, G. C., & Jorgenson, R. A. 2011, MNRAS, 412, 1047
de Souza, R. S., Yoshida, N., & Ioka, K. 2011, A&A, 533, A32
Dessart, L., Waldman, R., Livne, E., Hillier, D. J., & Blondin, S. 2013, MNRAS, 428, 3227
Djorgovski, S. G., Volonteri, M., Springel, V., Bromm, V., & Meylan, G. 2008, in The Eleventh Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Gravitation and Relativistic Field Theories, ed. H. Kleinert, R. T. Jantzen, & R. Ruffini (Singapore: World Scientific), 340
Ekstrã¶m, S., Meynet, G., Chiappini, C., Hirschi, R., & Maeder, A. 2008, A&A, 489, 685
Frebels, A., Aoki, W., Christlieb, N., et al. 2005, Natur, 434, 871
Frey, L. H., Even, W., Whalen, D. J., et al. 2013, ApJS, 204, 16
Fryer, C. L., Mazzali, P. A., Prochaska, J., et al. 2007, PASP, 119, 1211
Fryer, C. L., & Woosley, S. E. 1998, ApJL, 502, L9
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJL, 526, 152
Gal-Yam, A. 2012, Sci, 337, 927
Gal-Yam, A., & Leonard, D. C. 2009, Natur, 458, 865

14
