FINDING THE FIRST COSMIC EXPLOSIONS. IV. 90–140 $M_{\odot}$ PAIR-INSTABILITY SUPERNOVAE

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Received 2014 October 3; accepted 2015 February 25; published 2015 May 19

ABSTRACT

Population III stars that die as pair-instability supernovae are usually thought to fall in the mass range of 140–260 $M_{\odot}$. But several lines of work have now shown that rotation can build up the He cores needed to encounter the pair instability at stellar masses as low as 90 $M_{\odot}$. Depending on the slope of the initial mass function of Population III stars, there could be 4–5 times as many stars from 90–140 $M_{\odot}$ in the primordial universe as in the usually accepted range. We present numerical simulations of the pair-instability explosions of such stars performed with the MESA, FLASH, and RAGE codes. We find that they will be visible to supernova factories such as Pan-STARRS and LSST in the optical out to $z \sim 1–2$ and to James Webb Space Telescope and the 30 m class telescopes in the near-infrared (NIR) out to $z \sim 7–10$. Such explosions will thus probe the stellar populations of the first galaxies and cosmic star formation rates in the era of cosmological reionization. These supernovae are also easily distinguished from more massive pair-instability explosions, underscoring the fact that there is far greater variety to the light curves of these events than previously understood.

Key words: dark ages, reionization, first stars – galaxies: high-redshift – infrared: stars – stars: Population III – supernovae: general

1. INTRODUCTION

Pair-instability supernovae (PI SNe) are the most energetic thermonuclear explosions known and can be detected near the edge of the observable universe. They have now been studied by several groups for their potential to probe the properties of the first stars and galaxies (Greif et al. 2008, 2010, 2011, 2012; Johnson et al. 2009, 2014; Turk et al. 2009; Stacy et al. 2010, 2012; Clark et al. 2011; Hosokawa et al. 2011; Smith et al. 2011; Glover et al. 2013; Jeon et al. 2012; Susa 2013; Pawlik et al. 2011, 2013; Wise et al. 2012; Whalen et al. 2013; Hirano et al. 2014). They can also shed light on the origins of supermassive black holes and early cosmological reionization and chemical enrichment (Mackey et al. 2003; Whalen et al. 2004, 2008a, 2010; Abel et al. 2007; Smith & Sigurdsson 2007; Wise & Abel 2008; Alvarez et al. 2009; Tanaka & Haiman 2009; Smith et al. 2009; Park & Ricotti 2011, 2012, 2013; Volonteri 2012; Agarwal et al. 2012; Ritter et al. 2012; Whalen & Fryer 2012; Choi et al. 2013; Latif et al. 2013a, 2013b; Reisswig et al. 2013; Schleicher et al. 2013; Johnson et al. 2014; Chakki et al. 2013; Safranek-Shrader et al. 2014). For example, detections of both PI and core-collapse (CC) SNe at high redshift could be roughly binned by mass, thereby building up a simple Pop III IMF over time as enough events are discovered (de Souza et al. 2013, 2014). If the Pop III initial mass function (IMF) proves to be top heavy, this could account for the origins of SMBHs because enough 200–300 $M_{\odot}$ seed black holes might be formed at $z \sim 20$ for a few to reach $10^9$ $M_{\odot}$, by $z \sim 7$. If not, alternatives for SMBH seeds must be found, such as BHs forming by direct collapse in atomically cooled halos at slightly later epochs, $z \sim 10–15$ (Johnson et al. 2012, 2013b). PI SN candidates such as SN 2007bi (Gal-Yam et al. 2009; Kozyreva et al. 2014) and SN 2213–1745 (Cooke et al. 2012) have now been discovered at $z = 0.126$ and 2.05, respectively.

These studies have shown that 140–260 $M_{\odot}$ Population III (Pop III) PI SNe are visible in the near-infrared (NIR) at $z \gtrsim 30$ to the James Webb Space Telescope (JWST); Fryer et al. 2010; Kasen et al. 2011; Joggerst & Whalen 2011; Whalen et al. 2013a, 2013f, 2014; Hummel et al. 2012; Pan et al. 2012) (see also Heger & Woosley 2002; Kitayama & Yoshida 2005; Scannapieco et al. 2005; Whalen et al. 2008c; Chen et al. 2014a, 2014c). They, along with Pop III gamma-ray bursts (GRBs; e.g., Whalen et al. 2008b; Mesler et al. 2012, 2014; Nakauchi et al. 2012), will also be visible at $z \sim 10–20$ to the Wide-Field Infrared Survey Telescope (WFIRST) and Wide-field Imaging Surveyor for High Redshift, and at $z < 10$ to Euclid. Less energetic Pop III SNe will be visible to JWST at $z \sim 10–20$, depending on explosion type (Tominaga et al. 2011; Tanaka et al. 2012, 2013; Moriya et al. 2013; see also Johnson et al. 2013a; Whalen et al. 2013c, 2013d, 2013; Chen et al. 2014b, for new work on supermassive Pop III SNe).

This picture changes at higher metallicities. New explosion models of 150–500 $M_{\odot}$ PI SNe at LMC and SMC metallicities (Whalen et al. 2013b) have light curves that are quite different from those of zero-metallicity explosions, for two reasons. First, stars at these metallicities lose most of their mass to strong winds or outbursts that form structures around the star that can either quench or brighten emission from the shock.

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Mass loss also reduces the star to a compact He core by the time it dies, with ~1% of the original radius of the star. $^{56}$Ni yields and radiation diffusion timescales out of the ejecta are very different for explosions of bare He cores than for stars that retain their H envelope. Such explosions can therefore either be dim events that can only be seen in the local universe or superluminous events that are visible out to high redshifts. These new studies underscore the fact that there is far more variety to PI SN light curves than previously imagined.

How does rotation alter the energies and luminosities of Pop III PI SNe? It is now known that rotation can build up He cores massive enough to encounter the pair instability at stellar masses well below 140 $M_\odot$. Chatzopoulos & Wheeler (2012) (hereafter CW12) have shown that 90–135 $M_\odot$ Pop III stars can explode as PI SNe if they are born with rotation rates at 50% of the breakup velocity. They die as compact He cores because rotational mixing dredges heavier elements up to the outer layers of the star and drives mass loss. Their compact geometries guarantee that their light curves will be different from those of more massive stars that have retained their envelopes. Rotation can also induce bulging in the equators and flattening in the poles of such stars, which could introduce an azimuthal dependence to their light curves (Chatzopoulos et al. 2013).

How rotation affects the luminosities of ancient PI SNe is important because recent studies suggest that some massive Pop III stars may have been born with angular velocities close to the breakup limit (Greif et al. 2011; Stacy et al. 2013). Rotation may also have enabled much higher numbers of PI SNe at high redshift because 90–135 $M_\odot$ Pop III stars could be 4–5 times more numerous than those previously studied, depending on their IMF. Given their compact explosion geometries and variety of energies and $^{56}$Ni yields, can these events also probe the properties of the first stars? We have now modeled light curves and spectra for 90–135 $M_\odot$ PI SNe with the Los Alamos RAGE and SPECTRUM codes. In Section 2 we review our stellar evolution and initial explosion models along with our RAGE and SPECTRUM simulations. The blast profiles are examined in Section 3, and NIR light curves and detection limits for these explosions as a function of redshift are presented in Section 4. We conclude in Section 5.

2. NUMERICAL MODELS

We calculate light curves and spectra for PI SNe in five stages. First, the stars are evolved from the zero-age main sequence (ZAMS) in the MESA code up to the onset of the PI. At this point the models are mapped into the FLASH code and exploded. When nuclear burning is complete, typically within a few tens of seconds, we port the profile for the shock, the surrounding star, and the ambient wind into the RAGE code and evolve the SN out to 3 yr. We then post-process our RAGE profiles with the SPECTRUM code to construct light curves and spectra. Finally, these spectra are cosmologically redshifted and dimmed to obtain NIR light curves in the observer frame.

2.1. MESA/FLASH Simulations

The progenitor stars considered here are those from CW12, who studied the effects of rotation on the minimum masses of both pair-pulsational and PI SNe. These stars were evolved in the one-dimensional (1D) Lagrangian stellar evolution code MESA (Paxton et al. 2011, 2013), which includes a parametrized treatment of rotation and magnetic fields. How rotation induces mixing and angular momentum transport in these stars is discussed in detail in CW12. Although mass loss for highly evolved massive Pop III stars is not observationally constrained, it must be included because it can affect rotation by allowing the star to shed excess angular momentum over time as it evolves. In lieu of actual observations, we adopt the prescription of de Jager et al. (1988) and Vink et al. (2001) for mass loss from the stars in our models.

We modify this loss rate, which the star would have even if it was stationary, to account for rotation according to the method of Heger et al. (2000):

$$ \dot{m} = \dot{m}_{\text{rot}} / (1 - \Omega / \Omega_c)^{0.43}, $$

where $\dot{m}_{\text{rot}}$ is the mass-loss rate from de Jager et al. (1988) and Vink et al. (2001) and $\Omega$ is the surface angular velocity at the stellar equator. When $\Omega / \Omega_c = 1$ diverges, the mass loss timescale in MESA is limited to the thermal timescale of the star, $\tau_{\text{H}}$: $\dot{m} = \min(\dot{m}(\Omega), f \dot{m}/\tau_{\text{H}})$, where $f$ is an efficiency factor taken to be 0.3 (Yoon et al. 2010). To be consistent with Greif et al. (2011) and Stacy et al. (2013), we consider only stars that rotate at 50% of the breakup velocity at ZAMS. CW12 found that the minimum mass for a zero-metallicity PI SN progenitor at this initial rotation rate is $\sim 85$ $M_\odot$ (see also Yoon et al. 2012). Our grid of models therefore ranges from 90 to 140 $M_\odot$, in 5 $M_\odot$ increments. The stars all die as compact cores ($r_f \sim 10^{10}$–$10^{11}$ cm) that are H and, sometimes, He deficient.

In MESA, we adopt the Schwarzschild criterion for convection with $\alpha_{\text{MLT}} = 2$, the Timmes & Swesty (2000) “Helmholtz” equation of state (HELM EOS), which includes contributions from $e^+ e^-$ pairs, and the “approx21” nuclear reaction network (Timmes 1999), which has the $\alpha$-chain elements and the intermediate elements linking them through $(\alpha, p)/(p, \gamma)$ reactions from neutrons and protons all the way up to $^{56}$Ni (mass numbers $A$ from 1 to 56). The number of radial zones in the models was 800–1200 (the “mesh_delta_coeff” variable in MESA was set to 0.75–0.95). The stars are evolved from the ZAMS until the CO core encounters the PI and the CO core is driven past C/O burning as do CC SN progenitors.
The Astrophysical Journal, 805:44 (11pp), 2015 May 20

Table 1
PI SN Progenitor Properties

| \(M_*\) | \(r_f (\text{cm})\) | \(M_{\text{CO}}^a\) | \(M_{\text{Ni}}\) | \(E_{\text{vis}}\) (erg) |
|--------|----------------|----------------|----------------|----------------|
| 90     | 3.9e10         | 59.3           | 0.14           | 9.9e51         |
| 95     | 5.6e10         | 63.5           | 0.34           | 1.1e52         |
| 100    | 5.6e10         | 65.6           | 0.44           | 1.2e52         |
| 105    | 4.7e10         | 69.1           | 0.90           | 2.8e52         |
| 110    | 5.7e10         | 70.4           | 1.14           | 3.9e52         |
| 120    | 6.6e10         | 72.6           | 1.57           | 4.3e52         |
| 125    | 8.0e10         | 76.8           | 3.26           | 5.0e52         |
| 130    | 1.1e11         | 77.7           | 3.87           | 5.2e52         |
| 135    | 1.8e11         | 79.8           | 4.52           | 6.2e52         |
| 140    | 7.7e10         | 83.7           | 7.30           | 8.0e52         |

Note. All masses are in \(M_*\).

\(^aM_{\text{CO}}\) is the mass of the carbon–oxygen core defined within the radius where \(X_C + X_O > 0.5\).

Figure 1. Density and temperature structures of the stars prior to explosion. The thick black curve encloses the region where HELM EOS implies that \(\Gamma_{\text{adi}} < 4/3\), the PI regime. The dashed curves denote the structure of each star from 90 to 140 \(M_*\).

The angular velocities in the MESA models are set to zero in FLASH because Chatzopoulos et al. (2013) found that for a given CO core mass (and all else being equal), only extreme rotation can change PI SN energies and \(^{56}\text{Ni}\) production. Our models exhibit only modest degrees of rotation in the core when they reach the pair-instability regime (\(\Omega/\Omega_{c,\text{core}} \sim 0.02–0.06\)). We therefore only need to consider the effects of rotation on the structure of the star when evaluating its impact on light curves and spectra. We evolve the shock out just below the surface of the star. Terminating FLASH at this stage ensures that no photons from the shock have broken out of the surface of the star. Radiation transport is not required in this calculation because the mean free paths of the photons in the star are so short that they are simply advected along by fluid flows, but we include their contribution to the EOS.

2.2. RAGE

The explosion is evolved from breakout from the surface of the star out to 3 yr with the Los Alamos code RAGE (Gittings et al. 2008; Frey et al. 2013). RAGE is an AMR radiation hydrodynamics code with gray or multigroup flux-limited diffusion and a second-order conservative Godunov hydro scheme. RAGE uses Los Alamos OPLIB opacities\(^9\) (Magee et al. 1995) and includes multispecies advection and two-temperature radiation transport, in which matter and radiation temperatures, although coupled, are evolved separately. We include the self-gravity of the ejecta and point-mass gravity for any material that falls back to the center of the star. We evolve mass fractions for 15 elements: H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Ti, Cr, Fe, and Ni.

2.2.1. Model Setup

Our 1D spherical coordinate root grid has 100,000 uniform zones with an initial resolution that varies from \(4 \times 10^5 \text{ cm} \) to \(3 \times 10^6 \text{ cm} \). We set outflow and reflecting boundary conditions on the fluid and radiation flows at the inner boundary of the mesh (which is at 0 cm), respectively. Outflow conditions are set on the gas and radiation at the outer boundary. Up to two levels of refinement are applied to the initial interpolation of the profiles onto the setup grid and then during the simulation. We initialize radiation energy densities in RAGE from the temperatures in the FLASH profiles:

\[ e_{\text{rad}} = aT^4, \]

where \(a = 7.564 \times 10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4} \) is the radiation constant and \(T\) is the gas temperature. We also construct the specific internal energy from \(T\):

\[ e_{\text{gas}} = C_V T, \]

where \(C_V = 1.2472 \times 10^8 \text{ erg g}^{-1} \text{ K}^{-1} \) is the specific heat of the gas.

Our choice of mesh places the shock about a quarter of the way across the grid at launch. To accommodate the expansion of the ejecta and speed up the simulation, we resize the grid by a factor of 2.5 every \(10^6\) time steps or when the leading edge of the radiation front has crossed 90\% of the grid, whichever happens first. The time step on which the new series initially evolves scales approximately as the ratio of the new and old resolutions. We join a simple low-mass wind profile to the surface of the star:

\[ \rho_w(r) = \frac{\dot{m}}{4\pi r^2 v_w}, \]

where \(\dot{m}\) is the mass-loss rate of the wind and \(v_w\) is its speed. We take \(v_w\) to be 1000 km s\(^{-1}\) and the H and He mass fractions in the wind to be 76\% and 24\% for simplicity. The abrupt density drop between the star and wind is bridged by an \(r^{-2}\) density gradient to avoid numerical instabilities at shock breakout. We chose \(\dot{m}\) so that \(\rho_w \sim 2 \times 10^{-18} \text{ g cm}^{-3}\) at the bottom of the density bridge, so that it is optically thin there but still dense enough to prevent numerical instabilities in the radiation solution. The wind profile is continued outward until its density falls to that of the H II region of the star (e.g., Whalen et al. 2004). It is then replaced by the H II region, which is assumed to have a uniform density \(n = 0.1 \text{ cm}^{-3}\) and mass fractions of 76\% H and 24\% He.

We adopt a simple power-law wind profile because it is the next step up in complexity from a Pop III H II region, which would simply be a uniform density field with \(n \sim 0.1–1 \text{ cm}^{-3}\). The supposition of some residual wind is justified because of...
the mass loss exhibited by the stars over their lifetimes. Modeling shock breakout from the surface of the star into a diffuse H II region that is 19 orders of magnitude lower in density also presents severe challenges to the radiation solution in RAGE. We show density and velocity profiles for a few of our models in Figure 2.

2.3. SPECTRUM

We calculate a spectrum from a RAGE profile by mapping its densities, temperatures, mass fractions, and velocities onto a 2D grid in r and $\mu = \cos \theta$ in the Los Alamos SPECTRUM code. SPECTRUM directly sums the luminosity of each fluid element in the discretized profile to obtain the total flux escaping the ejecta along the line of sight at every wavelength. Our method, which is described in detail in Frey et al. (2013), includes Doppler shifts and time dilation due to the relativistic expansion of the ejecta and the intensities of emission lines. SPECTRUM also accounts for the attenuation of flux along the line of sight, capturing both limb darkening and absorption lines imprinted on the flux by intervening material in the ejecta and wind. Each spectrum has 14,899 energies.

Velocities, densities, mass fractions, and radiation temperatures are extracted from every level of the AMR hierarchy in RAGE and sequentially ordered by radius. Because of limitations on machine memory and time, only a subset of these data are mapped into SPECTRUM. We show density, temperature, and velocity profiles for the 90, 110, 130, and 135 $M_\odot$ PI SNe. Left: densities. Right: velocities.

3. EXPLOSION PROFILES

We show density, temperature, and velocity profiles for the a120 PI SN at shock breakout, at intermediate times, and at later times in Figure 3. As it breaks out of the surface of the compact core and descends the density bridge, the shock accelerates to $2.2 \times 10^{10}$ cm s$^{-1}$. As it approaches the bottom of the bridge, the shock begins to gradually slow down as it plows up the envelope. Within 1–2 s of breakout, photons that were previously advected along by the flow abruptly break free of the shock, as shown in the center left panel of Figure 3. The breakout transient is visible as the flat plateau in gas energy ahead of the shock at 7.2 and 9.8 s. This radiation front initially heats the gas to $500 \text{ eV}$. As the fireball expands, it cools by emitting radiation and performing work on the surrounding envelope. As it cools, its spectrum softens, and the temperature to which the radiation pulse heats the gas also decreases.

Spectroscopic luminosities for all 10 PI SNe in are shown in Figure 4. The duration of the breakout transient is greater than the light-crossing time of the star, in part because we assume the radiation remains partially coupled to the outer layers of the star that are blown off the pulse. As photons diffuse out through these outermost layers (the radiative precursor), they break free over a range of times and then become visible to an external observer. The opacity of the ejecta is also frequency dependent, so photons escape at different times according to their wavelengths (Bayless et al. 2014). As shown in Figure 4,
breakout luminosities vary from $\sim 10^{46}$ to $10^{47}$ erg s$^{-1}$, and they generally rise with explosion energy. Shock breakout also generally happens sooner in less massive stars because of their smaller radii. The breakout pulse itself is composed mostly of X-rays and hard UV. At $z \sim 20$ the pulse would last up to 1–2 days today, in principle making it much easier to detect at this epoch than in the local universe. But although it is also the most luminous phase of the SN, shock breakout is least visible at high redshifts due to absorption by the neutral intergalactic medium (IGM). Any X-rays that are not absorbed would be redshifted into the far-UV and absorbed in the outer layers of our Galaxy.

Radiation continues to drive the precursor ahead of the shock for $\sim 600$ s, as shown in the center panels of Figure 3. It is visible as the complex velocity and density structure at $2 \times 10^{12}$ cm at 302 s and $5 \times 10^{12}$ cm at 533 s. No strong reverse shocks form in the flow. The shock eventually overtakes and merges with the precursor because as it expands and cools it dims, and its flux can no longer sustain it. As shown in the panels on the right in Figure 3, the expansion of the flow is mostly...
homologous after $10^5$ s. All 10 PI SNe evolve through these stages in a similar manner.

At $10^5$–$10^7$ s, the SNe rebrighten as photons from $^{56}$Ni decay begin to diffuse out of the ejecta. The range in peak times is due to the range in diffusion times from the $^{56}$Ni layer to the surface for the progenitors in our study, with later times corresponding to larger ejecta masses. Peak luminosities rise with $^{56}$Ni mass, and the rebrightening typically lasts several hundred days in the rest frame of the SN. RAGE predicts somewhat lower $^{56}$Ni luminosities than SN codes that assume homologous expansion of the ejecta, as we show in Figure 5. Here, we plot bolometric luminosities for the a140 run calculated with the RAGE, Phoenix (van Rossum 2012), and STELLA (Blinnikov et al. 2006) codes. The Phoenix model is a 1D Lagrangian simulation with detailed $S_n$ radiative transfer in a homologously expanding medium with 125 zones in mass. The STELLA model is a 1D Lagrangian hydrodynamics simulation with 100 energy groups and 125 zones in mass.

As shown in Figure 5, Phoenix predicts peak $^{56}$Ni luminosities that are about an order of magnitude greater than those in RAGE. This discrepancy is most likely due to two factors. First, $^{56}$Ni rebrightening begins at about 70 days after the SN, by which time 75% of the total energy due to $^{56}$Ni and $^{56}$Co decay has been released ($\sim 1.3 \times 10^{51}$ erg for the 7.3 $M_\odot$ of $^{56}$Ni formed in the a140 explosion). In RAGE, this energy is first deposited as heat locally in the ejecta and then transformed into kinetic energy as the hot $^{56}$Co bubble performs $PdV$ work on its surroundings. After the heat is transformed into kinetic energy, it is difficult to recover it as luminosity later on when the $^{56}$Ni layer is exposed to the IGM, unless the ejecta crashes into some kind of circumstellar structure. This departure from the homologous expansion assumed in Phoenix is subtle because the total energy release due to radioactive decay is only 2% of the kinetic energy of the ejecta, but it results in significantly less luminosity during rebrightening.

The rebrightening in RAGE is therefore almost entirely due to $^{56}$Co decay after 70 days, which is $\sim 25\%$ of the total decay energy. On these numbers alone, one might expect the peak luminosity to be a factor of up to four lower in RAGE than in homologous expansion codes, which account for adiabatic expansion of the SN as a whole but do not capture the additional $PdV$ work done by the decay bubble. The additional factor of 2–3 less luminosity may be due to the lower density of the more expanded decay bubble in RAGE when it is exposed to the IGM. We also note that both Lagrangian models may not have fully resolved the flow of radiation through the PI SN ejecta, allowing more of it to escape than really does. When there are tens of thousands of optical depths in a given mesh point, numerical diffusion can allow photons to flow through the zone that should actually be absorbed. This may partially explain the discrepancy between RAGE and STELLA, which is also a radiation hydrodynamical calculation that does not assume homologous expansion. Opacities, minor differences in which can have substantial effects on luminosities, may also contribute to the differences between these two codes. More
tests are now underway to study both effects on $^{56}\text{Ni}$ luminosity in a variety of SNe.

4. NIR LIGHT CURVES/DETECTION LIMITS

Detections of SNe prior to the era of reionization ($z \gtrsim 6$) require observations in the NIR because any flux blueward of the Lyman limit at higher redshifts is absorbed by the partially neutral IGM. This likewise restricts detections in the optical to events at $z < 6$. All-sky surveys have the most potential to detect large numbers of high-$z$ SNe because their large survey areas can compensate for low star formation rates (SFRs) at early epochs (e.g., Figure 3 of Whalen et al. 2013e). But
extremely sensitive telescopes with more narrow fields such as JWST, the Thirty-Meter Telescope, the Giant Magellan Telescope, and the European Extremely Large Telescope are still expected to detect appreciable numbers of Pop III SNe (Hummel et al. 2012). We now consider detection limits in redshift for our PI SNe in the NIR for SNe at $z > 6$ and in the optical for events below this redshift.

We show optical and NIR light curves for the a90, a120, and a140 PI SNe in Figures 6–8 at low and high redshifts along with detection limits for JWST, WFIRST, and the SN factories: the Palomar Transient Factory (PTF), the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), and the Large Synoptic Survey Telescope (LSST). The light curves all have an initial short-lived transient that lasts up to $\sim50$ days. It

Figure 7. Light curves for the a120 PI SN at low redshifts (upper panels) and high redshifts (lower panels). In the upper four panels, $z = 0.01$ (dark blue), 0.1 (green), 0.5 (red), 1 (light blue), and 2 (purple). The horizontal dotted, dashed, and solid lines are photometry limits for PTF, Pan-STARRS, and LSST, respectively. In the lower four panels, $z = 4$ (dark blue), 7 (green), 10 (red), 15 (light blue), 20 (purple), and 30 (yellow). The horizontal dotted, dashed, and solid lines are photometry limits for WFIRST, WFIRST with spectrum stacking, and JWST, respectively.
is followed by a decline and then a second brighter and much
longer-lived phase that can last several hundred days or more
depending on the filter. This second broad peak is due to $^{56}\text{Ni}$
rebrightening. Detection limits in the NIR for these events vary
widely with mass and explosion energy but range from $a_{140}$
being visible to JWST out to $z \approx 7$–10 for 500–600 days to $a_{90}$
only being visible at $z < 7$. Only the most energetic SNe are
visible to WFIRST at $z \gtrsim 4$, and only if their spectra can be
stacked.
In the optical, detection limits in redshift vary from $z \sim 0.1$
for the $a_{90}$ PI SN to $z \sim 1$–2 for $a_{140}$. In the $g$, $r$, $i$, and $z$
bands the light curves exhibit similar rise and fall times at a given
redshift, but their durations increase with wavelength. They are
visible in these bands for 50–250 days and exhibit enough

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**Figure 8.** Light curves for the $a_{140}$ PI SN at low redshifts (upper panels) and high redshifts (lower panels). In the upper four panels, $z = 0.01$ (dark blue), 0.1 (green), 0.5 (red), 1 (light blue), and 2 (purple). The horizontal dotted, dashed, and solid lines are photometry limits for PTF, Pan-STARRS, and LSST, respectively. In the lower four panels, $z = 4$ (dark blue), 7 (green), 10 (red), 15 (light blue), 20 (purple), and 30 (yellow). The horizontal dotted, dashed, and solid lines are photometry limits for WFIRST, WFIRST with spectrum stacking, and JWST, respectively.
variation to be recognized as transients, given the short cadences of the factories. It is clear that the SN factories will be forming in pockets of metal-free gas (Trenti et al. 2009; Fumagalli et al. 2011). But determining whether or not such SNe are from Pop III stars would be problematic for several reasons. First, the high shock temperatures in these explosions would obscure the spectral lines that would differentiate these events from Pop II SNe. There are also degeneracies in light-curve structure between these SNe and the Pop III SNe of 0.1–0.3 $Z_\odot$ stars studied by Whalen et al. (2013b). By $z \sim 7$–10 most stars are expected to be contaminated by metals from the first few generations of SNe in the universe. Nevertheless, because these PI SNe can be easily distinguished from CC SNe, they can be used to probe the masses of stars in the era of first galaxy formation and reionization.

We note that once the redshift of a primordial SN is determined, typically by the spectroscopy of specific emission lines, discriminating between explosion types is relatively straightforward (e.g., de Souza et al. 2013, 2014). For example, 140–260 $M_\odot$ Pop III PI SNe are easily distinguished from CC SNe at the same redshift because of their much higher luminosities in the NIR and the longer duration of their light curves. Likewise, even if the PI SNe in this paper were visible among the first generation of stars, they are easily separated from 140–260 $M_\odot$ PI SNe whose progenitors retain their hydrogen envelopes because they too are much dimmer and have shorter durations. In principle, even the energetic explosions of other compact progenitors such as hypernovae can be distinguished from the explosions in this study because they have different emission times (Smidt et al. 2014). We illustrate these points by plotting NIR LCs for the a140 run, the 69.2 foe PI SN of a 250 $M_\odot$ Pop III red supergiant (Whalen et al. 2013f), a 2.4 foe 15 $M_\odot$ Pop III CC SN (Whalen et al. 2013b), and a 52 foe 25 $M_\odot$ hypernova (HN; Smidt et al. 2014) at $z = 15$ in Figure 9.

5. CONCLUSION

We find that 90–140 $M_\odot$ Pop III PI SNe whose progenitors have lost their H envelopes are only visible in the optical to PTF, Pan-STARRS, and LSST out to $z \sim 1$–2 but can be detected out to $z \sim 7$–10 by JWST and the coming generation of 30 m telescopes. These SNe fall into a now-familiar pattern for highly energetic explosions of compact, massive Pop III stars that have shed their outer envelopes. Although they exhibit very high luminosities and shock temperatures at breakout, 90–140 $M_\odot$ PI SNe, HNe (Smidt et al. 2014), and the PI SNe studied by Whalen et al. (2013h) are all much dimmer in the NIR at high redshift than 140–260 $M_\odot$ Pop III PI SNe with similar explosion energies, which can be detected at $z \gtrsim 30$ (Whalen et al. 2013f). None of the compact core Pop III SNe in these three studies can be seen at $z \sim 15$–20, the era of the first stars. Like the PI SNe considered here, HNe are only visible out to $z \sim 7$–10 to JWST and $z \sim 4$–5 to WFIRST, with detections of 0.1–0.3 $Z_\odot$ PI SNe by JWST being restricted to similar redshifts. However, they could all easily appear in future surveys of the first galaxies, which will be principal targets of JWST and the 30 m class telescopes.

This picture could change if ejecta from the explosion crashes into the mass lost by the star prior to its death, which can result in a superluminous SN like SN 2006gy. These events can be far brighter in the NIR than the original explosion (Smith et al. 2007; Moriya et al. 2010, 2013; Chevalier & Irwin 2011). Their high luminosities are due to the large radius of the shell upon impact, 1–2 AU. Much less energetic Type IIn SNe (1–2 foe) are visible to JWST at $z \sim 15$–20 and to WFIRST at $z \sim 7$ (Whalen et al. 2013g), so it is quite possible that the much more energetic collisions of the SNe in our study with shells may be visible to all-sky NIR missions out to $z \sim 10$–15. This would greatly increase their probability of detection at high $z$ because the wide survey areas of these missions could overcome low PI SN rates. We are now simulating such explosions with RAGE.

We have only considered PI SNe in very diffuse envelopes, in which all vestiges of the H layer have been driven beyond the immediate reach of the ejecta, as a first case. How this gas is actually distributed in radius around the star when it dies depends on how its mass loss evolved over time, and the impact of such profiles on SN light curves has only begun to be studied. The large number of possibilities for PI SN progenitor structure, metallicity, and envelope highlights the difficulty of matching any one PI SN candidate to current models. Studies to date have only considered red supergiants, blue compact giants, and stripped He cores. Stars of intermediate radius, such as yellow supergiants (YSGs), are only now being studied (see Kozyreva et al. 2014, who have found that the PI SN of a 250 $M_\odot$ YSG yields a bolometric light curve that is a good fit to SN 2007bi).

Although these less massive PI SNe will not be visible among the first generation of stars, they can be used to probe the stellar populations of the first galaxies and cosmic SFRs in the era of cosmological reionization. They, together with a growing number of other types of SNe, will soon open a direct window on star formation in the primeval universe.

D.J.W. acknowledges support from the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007-2013) via the ERC Advanced Grant “STARLIGHT: Formation of the First Stars” (project number 339177). E.C. would like to thank the Enrico Fermi Institute

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**Figure 9.** NIR light curves at 2.0 $\mu$m at $z = 15$ for a 250 $M_\odot$ Pop III PI SN (black), a 40 $M_\odot$ CC SN (red), a 25 $M_\odot$ HN (blue), and the a140 PI SN (green).
