Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Detecting the First Supernovae in the Universe with JWST

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Abstract. Massive Population III stars die as pair-instability supernovae (PI SNe), the most energetic thermonuclear explosions in the universe with energies up to 100 times those of Type Ia or Type II SNe. Their extreme luminosities may allow them to be observed from the earliest epochs, revealing the nature of Pop III stars and the primitive galaxies in which they reside. We present numerical simulations of Pop III PI SNe done with the radiation hydrodynamics code RAGE and calculations of their light curves and spectra performed with the SPECTRUM code. We find that 150 - 250 $M_\odot$ PI SNe will be visible to the James Webb Space Telescope (JWST) out to $z \sim 30$ and to $z \sim 15 - 20$ in all-sky NIR surveys by the Wide Field Infrared Survey Telescope (WFIRST).

Keywords. early universe – stars:early type – galaxies:high-redshift – supernovae:general – methods:numerical

1. Introduction

The first stars in the universe are thought to form at $z \sim$ 20 - 30 in 10^5 - 10^6 $M_\odot$ cosmological halos (Bromm *et al.* 2001, Nakamura & Umemura 2001, Abel *et al.* 2002). Numerical models suggest that they are 20 - 500 $M_\odot$ (O'Shea & Norman 2007) and form one per halo, in binaries (Turk *et al.* 2009), or in small multiples of up to a dozen (Clark *et al.* 2011, Stacy *et al.* 2010, Greif *et al.* 2011). Their extreme ionizing luminosities (Schaerer 2002) create large H II regions and expel most of the gas from the halo (Whalen *et al.* 2004, Kitayama *et al.* 2004, Alvarez *et al.* 2006, Abel *et al.* 2007). Pop III stars are central to understanding the nature of primeval galaxies, early cosmological reionization and chemical enrichment, and the origin of supermassive black holes. Unfortunately, although they are very bright individual Pop III stars lie beyond the realm of direct detection by current and upcoming surveys.

The final fates of Pop III stars primarily depend on their main sequence masses at birth. If their masses are 140 - 260 $M_\odot$, they die in spectacular thermonuclear explosions known as pair-instability supernovae, with energies up to 100 times greater than those of Type Ia or Type II SNe (Heger & Woosley 2002). Such explosions completely unbind the star, leaving no compact remnant. Because they can be hundreds of thousands of times brighter than their progenitors, Pop III PI SNe are prime candidates for detection by upcoming missions such as JWST and WFIRST that would directly probe the Pop III IMF for the first time. However, unlike Type Ia SNe now being used to constrain cosmic acceleration, photons from Pop III SNe must traverse the Lyman alpha forest, the vast tracts of intervening neutral hydrogen clouds and filaments that absorb or scatter most of them out of our line of sight. Numerical predictions of their detection therefore require absorption by the Lyman alpha forest in addition to cosmological reddening and accurate

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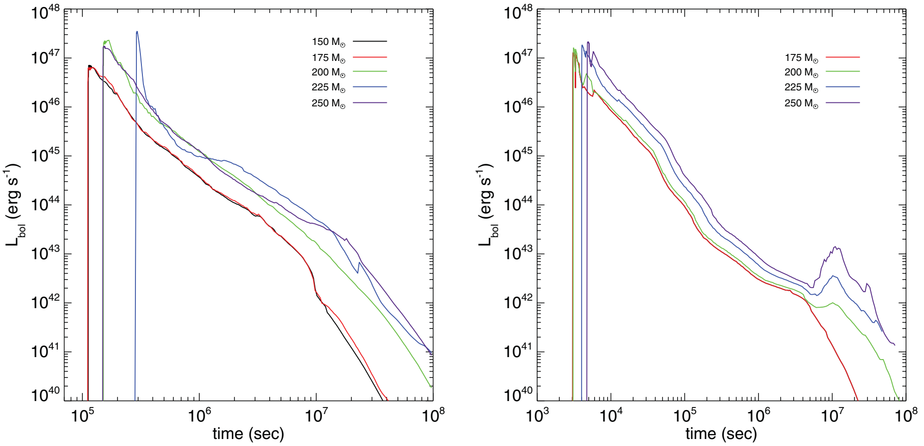

Figure 1. Rest frame bolometric luminosities for all 9 PI SNe out to 3 yr. Left panel: u-series. Right panel: z-series.

light curves (see Scannapieco *et al.* 2005, Joggerst & Whalen 2011, Kasen *et al.* 2011, and Pan *et al.* 2011 for earlier studies of PI SNe at low redshift).

We present numerical simulations of Pop III PI SNe and their light curves and spectra with the Los Alamos National Laboratory (LANL) RAGE and SPECTRUM codes. We convolve our spectra with cosmological reddening, absorption by the Lyman alpha forest according to the prescription of Madau 1995 and Su *et al.* 2011, and instrument filters to find detection thresholds in redshift for JWST and WFIRST.

2. RAGE/SPECTRUM

RAGE (Radiation Adaptive Grid Eulerian) is a multidimensional adaptive mesh refinement (AMR) radiation hydrodynamics code that couples second-order conservative Godunov hydrodynamics to grey or multigroup flux-limited diffusion to simulate strongly radiating flows (Gittings *et al.* 2008). RAGE utilizes the extensive LANL OPLIB database of atomic opacities† (Magee *et al.* 1995). We describe the physics implemented in our RAGE runs and why it is needed to capture the features of our light curves in Fryer *et al.* 2010 and Frey *et al.* 2012: multispecies advection, grey FLD radiation transport with 2T physics, energy deposition from the radioactive decay of ^{56}Ni, and no self-gravity. We include mass fractions for 15 elements, the even numbered elements predominantly synthesized in PI SNe. We post-process RAGE profiles with the SPECTRUM code to obtain spectra with 14900 energies. SPECTRUM accounts for Doppler shifts and time dilation due to the relativistic expansion of the ejecta and calculates intensities of emission lines and the attenuation of flux along the line of sight with monochromatic OPLIB opacities. Our spectra thus capture both limb darkening and the absorption lines imprinted on the flux by intervening material in the ejecta and wind.

3. Pop III PI SN Light Curves

We show bolometric luminosities for 150, 175, 200, 225 and 250 M$_\odot$ Pop III PI SNe in Figure 1. U-series progenitors are red hypergiants and z-series progenitors are compact blue giants. Total luminosities at shock breakout typically exceed 10^{47} erg/s and are primarily x-rays in the z-series and both x-rays and hard UV in the u-series. Radiation

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† http://aphysics2/www.t4.lanl.gov/cgi-bin/opacity/tops.pl

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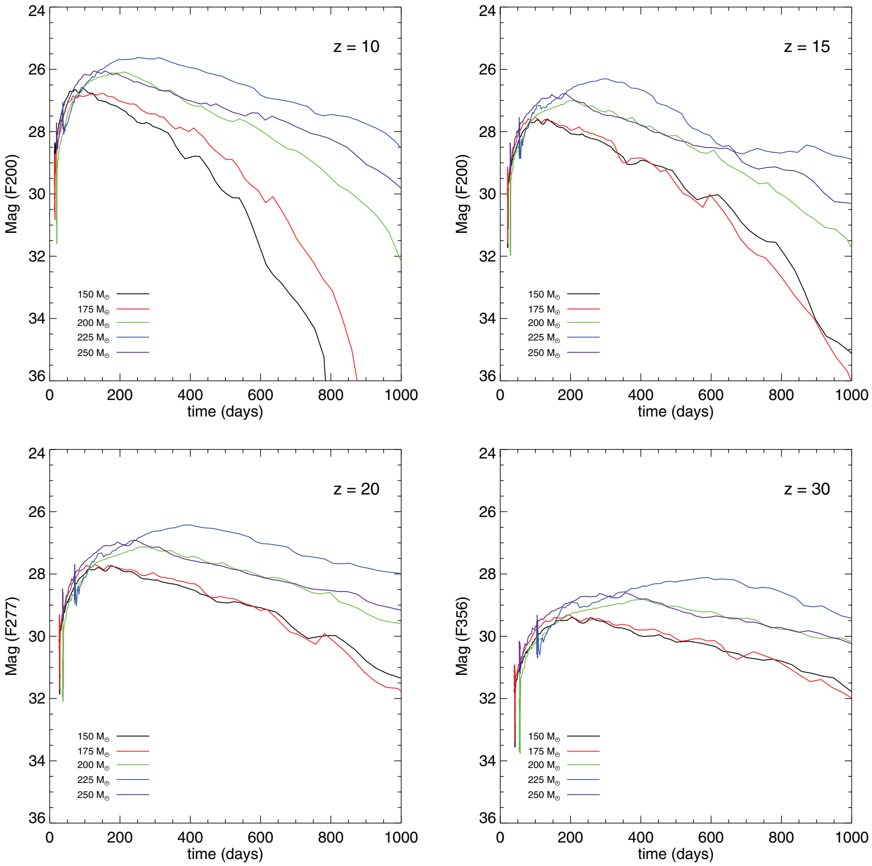

Figure 2. Pop III u-series PI SN light curves for the *JWST* NIRCam. The optimum filter for each redshift is noted on the y-axis labels and the times on the x-axes are for the observer frame.

temperatures at breakout are lower in the u-series because the shock must do more PdV work on its surroundings prior to exiting the star than in the z-series. U-series PI SNe exhibit a more extended plateau in luminosity than z-series explosions that is reminiscent of Type II-p SNe, whose progenitors are also though to be red giants. In general, z-series explosions are somewhat dimmer than u-series explosions of the same mass because they manufacture significantly less ^{56}Ni, whose decay powers the light curves at intermediate to late times. The resurgence in luminosity at $\sim 10^7$ s occurs when the photosphere descends into the hot ^{56}Ni layer in the frame of the ejecta. This feature is present in both series but is less evident in the u-series because luminosities before and after the bump are greater.

Our Pop III PI SN bolometric luminosities are ~100 times those of Type Ia and II SNe because of their much greater explosion energies and because they synthesize up to 50 M$_\odot$ of ^{56}Ni, in contrast to Type Ia SNe that create ~1.5 M$_\odot$. Also, PI SNe remain bright for up to 3 yr, rather than 3 - 5 months. This is primarily due to the longer radiation diffusion timescales in the much more massive ejecta:

$$t_d \sim \kappa^{\frac{1}{2}} {M_{ej}}^{\frac{3}{4}} E^{-\frac{3}{4}}, \qquad (3.1)$$

where κ is the average opacity of the ejecta, M_{ej} is the mass of the ejecta, and E is the explosion energy.

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4. JWST/WFIRST Detection Thresholds

We show JWST NIRCam light curves at 2.0, 2.0, 2.77 and 3.56 μm at $z = 10$, 15, 20 and 30, respectively, for our five u-series SNe in Figure 2. Given that $z \sim 20$ light curves would be stretched to nearly 60 yr in duration in the earth frame, one might think that PI SNe at that epoch would not appear as transients today. However, the expansion and cooling of the fireball in the rest frame creates an NIR flux in the earth frame that varies over 1000 days, the typical duration of a high-redshift protogalactic survey. NIRCam photometry detection thresholds for deep surveys are mag 31 - 32, so it is clear that JWST will detect PI SNe out to $z \sim 30$ and even perform spectroscopy on them.

While JWST might be sensitive enough to detect $z \sim 30$ SNe, are its search fields too narrow to encounter one in its operational lifetime? New calculations indicate that a few Pop III PI SNe will be present NIRCam surveys at any given time (Hummel *et al.* 2011). Furthermore, as can be seen in the $z = 15$ and 20 panels above, WFIRST, with its proposed sensitivity of mag 26.5 at 2.2 μm, will detect Pop III PI SNe at $z = 15$ - 20 in much greater numbers in all-sky surveys. The detection of the first supernovae in the universe will be one of the most spectacular results in extragalactic astronomy in the coming decade, unveiling for the first time the stars that ended the cosmic Dark Ages.

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Discussion

Nomoto: If the core-collapse supernova is a hypernova with an energy of 3×10^{52} erg, up to what redshift can such an explosion be observed with JWST?

Whalen: Preliminary simulations suggest that 15 - 40 $M_\odot$ Pop III core-collapse supernovae will be visible in the NIR out to $z \sim 7$ with JWST. My guess is that hypernovae could be seen out to $z \sim 10$ - 15. They would be an exciting discovery because this is the era of protogalaxy formation, and such SNe would reveal the positions of primeval galaxies on the sky.

Ioka: How do you find Pop III SNe? The FOV of JWST is not large.

Whalen: Recent calculations by Hummel *et al.* (2011) suggest that Pop III PI SN rates at $z \sim 20$ will ensure that a few are present in any given JWST search field over typical survey times. We also find that the Wide-Field Infrared Survey Telescope (WFIRST), with its proposed sensitivity of 26.5 mag at 2.2 μm, will be able to see PI SNe out to $z \sim 15$ - 20 and would detect much larger numbers of such events. In fact, this redshift range may be optimal for detecting PI SNe because of the rise of Lyman-Werner UV H_2 photodissociating backgrounds from the first generations of Pop III stars. The LW background is thought to suppress Pop III star formation in minhalos until they have grown to larger masses that likely result in more massive stars at slightly lower redshifts (see O'Shea & Norman 2008).

Couch: Do the shock breakout light curves account for light travel time effects across the surface of the star?

Whalen: They do to an extent because the radiation flow is calculated in 1D spherical geometry with flux-limited diffusion. A higher-order transport method such as implicit Monte Carlo would do a better job of this because it better captures the angular dependence of the radiation field. However, radiation – matter coupling effects prevent all the photons from exiting the shock at once when it breaks through the surface of the star and broaden the light curve by several light-crossing times, effectively erasing light-crossing time effects.

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