Detecting Pair-instability Supernovae at z \lesssim 5 with the James Webb Space Telescope

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Abstract

Pair-instability supernovae (PISNe) are the ultimate cosmic lighthouses, capable of being observed at z \gtrsim 25 and revealing the properties of primordial stars at cosmic dawn. But it is now understood that the spectra and light curves of these events evolved with redshift as the universe became polluted with heavy elements because chemically enriched stars in this mass range typically lose most of their hydrogen envelopes and explode as bare helium cores. The light curves of such transients can be considerably dimmer in the near-infrared today than those of primordial PISNe of equal energy and progenitor mass. Here, we calculate detection rates for PISNe whose progenitors lost their outer layers to either line-driven winds or rotation at z \lesssim 10, their detection limit in redshift for the James Webb Space Telescope (JWST). We find that JWST may be able to detect only Population II (metal-poor) PISNe over the redshift range of z \lesssim 4, but not their Population III (metal-free) counterparts.

Unified Astronomy Thesaurus concepts: Early universe (435); Supernovae (1668)

1. Introduction

Stars with masses of 90–260 M_\odot at the end of their lives are expected to encounter the pair instability (PI), in which temperatures and densities in their cores favor the production of positron–electron pairs (Barkat et al. 1967; Rakavy & Shaviv 1967). Pair production comes at the expense of thermal photons and thus pressure support in the core, causing it to contract and its temperatures to rise, which in turn produces more rapid burning, positron–electron pairs, and core contraction. Eventually this process triggers explosive burning in the O and Si layers that is capable of completely destroying the star in a highly energetic thermonuclear supernova (SN; Heger & Woosley 2002; Joggerst & Whalen 2011; Chen et al. 2014a, 2014b).

With energies of up to 100 times those of Type Ia SNe, Population III PISNe can be detected at z \gtrsim 25, revealing the properties of the first stars in the universe (Whalen et al. 2013a, 2013c, 2013e, 2014a). In contrast, JWST will not detect core-collapse (CC) SNe beyond z \sim 10–15 (Whalen et al. 2013d). Although Type II SNe and gamma-ray bursts (GRBs) could be observed at z \sim 20–25, there may be far fewer of them than PISNe at these epochs, depending on the Population III initial mass function (IMF; Whalen et al. 2013b; Mesler et al. 2014).

But the spectra and light curves of PISNe could have changed significantly with the metallicity of the progenitor star as the universe gradually became polluted by SNe over cosmic times. Higher metallicities lead to larger mass-loss rates due to line-driven winds that can strip much of the H layer from the star by the time it encounters the PI (Langer et al. 2007; Yoon et al. 2012; rotation can have a similar effect—Chatzopoulos & Wheeler 2012a, 2012b; Chatzopoulos et al. 2013, 2015). The star is therefore much more compact at death, with explosion light curves that are quite different from those of Population III PISNe. Simulations show that spectra of high-z PISNe whose progenitors have lost at least part of their outer layers are much dimmer in the NIR today than Population III PISNe of equal energy and mass because the fireball cools to temperatures at which its emission peaks in the NIR at much smaller radii (Smidt et al. 2014, 2015; Whalen et al. 2014b). Consequently, it can be more difficult to observe PISNe at z \lesssim 10 than at z \sim 20.

What then are the prospects for detecting PISNe at these lower redshifts in the coming decade with JWST and ground-based extremely large telescopes (ELTs)? Although they are dimmer, there may be more of them because of the rise in cosmic star formation rates (SFRs) at z \sim 10 inferred from the luminosity functions of early galaxies (Campisi et al. 2011), from GRB rates (Ishida et al. 2011; Robertson & Ellis 2012), and from simulations (e.g., Wise et al. 2012; Hasegawa & Semelin 2013; Johnson et al. 2013; Muratov et al. 2013; Pawlik et al. 2013; Xu et al. 2013, 2016; Magg et al. 2016). Previous estimates of PISN detection rates out to z \sim 20 (Scannapieco et al. 2005; Weinmann & Lilly 2005; Wise & Abel 2005; Hummel et al. 2012; Pan et al. 2012; Tanaka et al. 2012; de Souza et al. 2013, 2014; Hartwig et al. 2018; Rydberg et al. 2020; Moriya et al. 2019) may be too high at z \lesssim 10 because they all used light curves of Population III explosions, which are much brighter than the more realistic spectra of explosions of partially stripped stars.

Although only a few PISN candidates have been found at low redshifts to date (Gal-Yam et al. 2009; Cooke et al. 2012; Kozyreva et al. 2018) the unprecedented sensitivities of JWST and the ELTs could reveal far more of them, probing SFRs at higher redshifts than ever before as well as the stellar populations of the first galaxies. Here, we calculate detection rates for PISNe at z \lesssim 10 for JWST for compact progenitors that have lost some of their envelopes to either line-driven winds or rotation. In Sections 2–3 we describe our PISN spectral models and how they are cosmologically dimmed, redshifted, and convolved with filter functions, and we describe cosmic SFRs in Section 4 to obtain detection rates. In Section 5 we discuss these rates and conclude in Section 6. Some of our light curves are in the Appendix.

2. Numerical Method

Our source frame spectra for z \lesssim 10 PISNe (essentially, bare He cores) were calculated in three stages. First, the progenitor
star was evolved from the zero age main sequence to the onset of the PI, explosion, and the end of all thermonuclear burning in the GENEVA and KEPLER codes (Woosley et al. 2002; Eggenberger et al. 2008) and in the MESA and FLASH codes (Fryxell et al. 2000; Dubey et al. 2009; Paxton et al. 2011, 2013). Each SN was then evolved from shock breakout from the surface of the star to expansion into the IGM with the Los Alamos radiation hydrodynamics code RAGE (Gittings et al. 2008). All explosions were evolved for 3 yr after breakout. RAGE profiles for the PI SNe were then post processed with the Los Alamos SPECTRUM code to obtain spectra for the fireball in the rest frame (Frey et al. 2013).

We consider two sets of progenitors: 0.14–0.43 Z⊙ 150–500 M⊙ stars that have lost their hydrogen layers to strong winds (Whalen et al. 2014b) and 90–140 M⊙ Population III stars that have lost their outer envelopes to rotation (Smidt et al. 2015). We adopt the spectra for the explosions in low densities in Whalen et al. (2014b) to obtain upper limits to their luminosities in the NIR today. The properties of both sets of PISNe (progenitor mass, metallicity, explosion energy, and 56Ni yields) are summarized in Table 1 of their respective papers, where we also lay out in detail our stellar evolution and burn models, radiation hydrodynamical simulations, and spectrum calculations (see Kasen et al. 2011; Dessart et al. 2013; Kozyreva et al. 2014a, 2014b; Jerkstrand et al. 2016; Gilmer et al. 2017; Kozyreva et al. 2017, for other PI SN light curves for a variety of progenitor metallicities and rotation rates).

Metals lead to mass loss, which reduces the diffusion timescale. A dense circumstellar envelope increases diffusion timescales by contributing to mass. Population III stars explode in low-density relic H II regions while PISNe in the local universe may occur in dense winds and bubbles blown by the star. Collision with prior outburst also adds to the luminosity.

Most important for estimating metallicity thresholds for PISNe are the mass loss rates of very massive stars during their evolution. Georgy et al. (2017) find that H-rich PISN could occur at metallicities as high as Z⊙/3 (lower for rotating). Magnetic field could suppress mass loss even for higher (solar) metallicity. About 7% of O-stars have important surface dipolar magnetic field at solar metallicity. Such surface magnetic fields can quench the mass loss from the star (Petit et al. 2017). This mechanism can form PISNe at higher metallicity than usually thought, and could explain SLSNe in the local universe.

The 150 and 200 M⊙ Population II models have metallicity Z = 0.14 Z⊙ corresponding to the Small Magellanic Cloud. The 500 M⊙ model has metallicity Z = 0.43 Z⊙ corresponding to the Large Magellanic Cloud.

3. JWST Magnitudes and Colors

3.1. Observational Constraints

In this paper we consider the observational conditions of the First Lights at REionization (FLARE) project as proposed by Wang et al. (2017). FLARE intends to discover and classify luminous transients above z > 2 redshifts utilizing repeated deep observations with JWST NIRCam within the JWST Continuous Viewing Zone near the North Ecliptic Pole (NEP). The total area of the 3 yr long survey is ~300 arcmin², which will be monitored in 4 NIRCam filters (F150W, F200W, F356W, and F440W) with a ~3 month cadence. With the proposed conditions the limiting magnitude for a ~3σ detection will be ~27 AB-mag. See Wang et al. (2017) and Regős & Vinkó (2019) for more details.

3.2. Light Curves

In Figure 1 (upper panel) and Figure 2 (upper panel) (and Figures A1 and A2 in the Appendix) we show synthetic light curves of zero metallicity Population III PISN models in the F150W, F200W, F356W, and F440W NIRCam filter band-passes for 150 M⊙ and 200 M⊙ (and 175 M⊙, 225 M⊙, and 250 M⊙) progenitors, respectively. Different redshifts up to z = 10 are color-coded, and the time since explosion is expressed in observer’s frame days. These light curves were calculated by convolving the time-dependent spectra of these model SNe with the bandpass functions of the NIRCam filters, after redshifting and scaling them by the luminosity distance. We adopted the standard Λ-CDM cosmology with the following parameters: Ωm = 0.315, ΩΛ = 0.685, and H0 = 67.4.

As seen in these figures, Population III PISNe just barely reach the ~27 mag detectability limit for z < 4 events and escape detection in all JWST/NIRCam filters at higher redshifts. Usually PISNe are expected to occur at redshifts higher than this limit, i.e., at z > 6. However, if there were some Population III stars formed at lower redshift (i.e., at later epochs on the cosmic timescale) than the majority of them, JWST might detect a few of those.

In addition to Population III models, massive stars with Population II chemical composition may also produce PISNe. Population II and Population III models may have quite different colors and spectra due to primarily the presence of metals in the ejecta of the Population II events. In addition, Population II PISNe do not suffer from strong Lyman α absorption in the intergalactic medium, although this depends on redshift, i.e., on the ionization degree of the intergalactic medium.

Figure 1 (lower panel) and Figure 2 (lower panel) exhibit light curves of Population II (Z = 0.14 Z⊙, metallicity, low-density envelope) models assuming 150 and 200 M⊙ progenitor masses, respectively.

Figure 1 is a direct comparison of PISN light curves from Population II and Population III (for 150 M⊙). While the upper panel is metal free, the lower panel shows PISNe from metal enriched stars for the detection with JWST. Figure 2 is the same comparison of Population II and Population III (as Figure 1) for 200 M⊙.

In addition, we also examine the Population II, Z = 0.07 Z⊙ model of Chatzopoulos et al. (2019) with 250 M⊙ progenitor mass. Peak AB-magnitudes from the latter model as a function of filter wavelength, color-coded for different redshifts, are shown in Figure 3.

Figure 4 displays peak magnitudes of the Population II, Z = 0.14 Z⊙ model (Whalen et al. 2014b) as a function of filter wavelength and redshift.

It is seen in Figure 3 that Population II, Z = 0.07 Z⊙ PISNe of 250 M⊙ (Chatzopoulos et al. 2019) may be detected between 1 < z < 4 redshifts in the FLARE survey, if we assume ~27 AB-mag as the 3σ detection limit in all filters. This is different from the case of the zero metallicity Population III PISNe, because the peak magnitudes of the simulated light curves of the latter seem to be somewhat fainter (see also Figures 1 and 2, lower panels).
Figure 1. Light curves of 150 \( M_\odot \) PISN models at various redshifts and JWST filter wavelengths. Upper panel: Population III (zero metallicity) model; lower panel: Population II, \( Z = 0.14 Z_\odot \) model.
Nevertheless, both sets of light curves show very slow evolution: they are expected to stay near maximum light for an order of $\sim 100$ days. Time dilation stretches with a factor of $1 + z$ in the observer’s frame, causing visibility at higher redshifts. This will increase the detection probability for such events, because if such a transient is detected within the survey

Figure 2. Same as Figure 1 but for 200 $M_{\odot}$ models.
and high redshifts remains possible. They do, however, preserve the redshift-dependent colors; therefore, the separation of transients at low redshifts can be likely immediate to eliminate foreground objects. For example, Tanaka et al. (2013) suggested the application of F200W–F277W versus F277W–F356W as a diagnostic tool for discovering SLSNe. More recently, Regős & Vinkó (2019) found that Type Ia SNe at z > 1 redshifts can be likely identified on the F200W–F444W versus F150W–F356W color–color diagram.

The position of PISNe having Population III as well as Population II metallicity are plotted on the F200W–F444W versus F150W–F356W color–color diagram in Figure 5. Population II/Population III PISNe are represented by magenta/red symbols, respectively. Each symbol corresponds to a 150 (Population III) or 250 (Population II) M☉ model around maximum light but at different redshifts between z = 1 and 10. Also shown are the various types of SNe modeled by Regős & Vinkó (2019).

It is seen that Population II PISNe occupy nearly the same range on the color–color plot as the SLSNe, which is not unexpected as both types of transients are thought to have originated from very massive progenitors. Population III PISNe are clustered in a small region located in the middle of the area occupied by the hydrogen-poor SNe Ia and Ib/c, thus, metal-free PISNe, if they were observable, would look nearly the same as the Type Ia or Ib/c SNe at lower redshifts. This means that the contamination by low-redshift transients will probably be a serious observational challenge, at least as far as the identification of Population III PISNe is concerned.

High-redshift observations of time domain astronomy are less demanding on cadence than local ones due to the time dilation, and NEP revisits can be proposed with normal STScI planned annual cycles. Spectroscopic follow-up of targets of opportunity with NIRSPEC and ELT instruments may also be a modest imposition on these facilities. Deep ground-based reference fields at shorter wavelengths should be initiated immediately to eliminate foreground objects (see Wang et al. 2017). The Subaru Strategic Program (Aihara et al. 2018) is a model for such data and adding the NEP to the current fields is a way to do it. X-ray follow-up of JWST high-redshift transients will also be vital. Spectroscopic follow-up can help us to identify and distinguish PISNe from other sources.

Unambiguous spectral identification at any redshift is unlikely. A light curve could be more discriminant if the inferred nickel mass was high. There has not been any candidate event that sufficiently matches PISN model spectra. If one event was found to match any model spectra, that would be a strong case. Observation of a model matching spectrum would indicate a PISN. There are many neutral lines in the spectra: Fe, Si, and O, as well as Ca II, Mg II, and S II. In

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**Figure 3.** Peak magnitudes of Population II, Z = 0.07 Z☉, PISN models of 250 M☉ by Chatzopoulos et al. (2019) at various redshifts as a function of NIRCam filter wavelength.

**Figure 4.** Peak magnitudes of Population II, Z = 0.14 Z☉, PISN models of 200 M☉ (Whalen et al. 2014b) at various redshifts as a function of NIRCam filter wavelength.

**Figure 5.** JWST color–color diagram of Population II (magenta) and Population III (red symbols) PISNe and various other types of SNe around maximum light. The position of SNe Ia (circles), Ib/c (asterisks), II-P (squares), and SLSNe (triangles) on the JWST color–color (F200W–F444W vs. F150W–F356W) diagram. Type Ia SNe are shown as circles, while the squares, crosses, and asterisks indicate the low-redshift Type II-P and Ib/c SNe that may contaminate the observed sample.
general, lower mass events have more lines (a forest of lines, Jerkstrand et al. 2016). Mixing affects spectroscopic and color evolution. Strong features of intermediate mass elements dominated by silicon, magnesium, and oxygen reach intensities that depend on the extent of mixing.

4. PISN Rates

4.1. Rates of Population II and Population III Events

Theoretical models of star formation suggest there is a transition from metal-free Population III to metal-rich Population I–II star formation. This transition occurs at $z > 3$–4 (Tornatore et al. 2007; Trenti et al. 2009; Maio et al. 2010). There remain pristine regions where Population III star formation and PISN prevail in patches even around redshifts $z \sim 3$. The metal enrichment is competing against cosmological expansion, so the pockets of metal-free gas remain isolated to some extent. Still, even these pockets are polluting themselves. JWST will help to constrain how long Population III star formation continues.

The Population III SFR itself depends upon the PISN rate (Maio et al. 2010). Their simulations show that it is rather independent from many parameters, e.g., the critical metallicity (at which metal cooling dominates over the molecular Lyman–Werner background) for transition, IMF slope and range, SN/PISN yields, or star formation threshold.

4.2. Effects of the Initial Mass Function (IMF)

As massive stars have short life times, which can be approximated as $\sim 30 \times (M/8 M_\odot)^{-2.5}$ Myr, the PISN rate, $\dot{n}$, traces the SFR as a function of cosmic time or redshift.

For a particular mass range and explosion type

$$\dot{n}_{\text{SN}}(z) = \text{SFR}(z) \times \frac{\int_{M_{\text{min}}}^{M_{\text{max}}} \Psi(M) dM}{\int_{15 M_\odot}^{500 M_\odot} M \Psi(M) dM},$$

where $\Psi(M)$ is the IMF (de Souza et al. 2014).

We assume that the IMF is either Salpeter, i.e., $dN/dM \propto M^{-2.35}$ or flat, $dN/dM = \text{const}$. These choices are motivated by cosmological simulations. The lower and upper mass limits for PISN are $M_{\text{min}} = 140 M_\odot$, $M_{\text{max}} = 260 M_\odot$, or for Population III may be down to $M_{\text{min}} = 85 M_\odot$ if they are rapidly rotating (Chatzopoulos & Wheeler 2012a).

4.3. Effects of the SFR

For Population II (metal-poor) progenitors we assume that the cosmic SFR is similar to the one used in many previous studies, e.g., in Hopkins & Beacom (2006). The IMF is Salpeter in these Population II models, and the PISN mass limits are 140 and 260 $M_\odot$ as above.

For Population III (metal-free) stars the SFR is mostly known from simulations (e.g., de Souza et al. 2014) with some observational hints. We assume a flat IMF for such progenitors, and $M_{\text{min}}$ can be chosen as $85 M_\odot$ (Chatzopoulos & Wheeler 2012a).

For Population III, according to de Souza et al. (2011), Wise et al. (2012), and Xu et al. (2013), by $z \sim 15$ the SFR is $\sim 10^{-4} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$. Xu et al. (2013) predict $<10^{-5} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ by $z \sim 8$ (and flat from $z \sim 17$). Bouwens et al. (2014) constrain SFR $\sim 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$, lower than Population II but probably higher than Population III. In Yang et al. (2015), Figure 2 indicates a maximum of $\sim 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ for the SFR.

Models of Population III have at least an order of magnitude smaller SFRs than those of Population II. For Population III.2, which is primordial but irradiated by other stars, Bouwens et al. (2014) display $\lesssim 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z \sim 7$ and $\sim 2 \times 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z \sim 5$.

Theory predicts $\sim 10^{-3} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ for Population III.2 at $z \sim 5$ (~40 Population II) and $\sim 10^{-2.5} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ by $z \sim 7$ (a larger Population II ratio).

Figure 6 is an overview of the various star formation rate densities as function of redshift (Population III, Population III.2, and Population II). The red markers at $z > 5$ are from Xu et al. (2015), the lower blue triangle at $z = 5$ is from Yang et al. (2015). The rest of the symbols are Bouwens et al. (2014).

4.4. Normalization

The Population III PISN rates were calculated with a semianalytical model that utilizes a cosmologically representative set of halo merger trees with detailed prescriptions for radiative and chemical feedback on star formation in the halos (Ryderberg et al. 2010; Hartwig et al. 2015; Magg et al. 2016). This model assumes flat IMF.

While the integration over the mass function in Equation (1) is not very sensitive to the normalization by the IMF lower mass limit in the denominator for flat IMF for Population III stars, for the Salpeter IMF for Population II it is. Weinmann & Lilly (2005) integrate the IMF between 0 and infinity and consider bimodality, but see other constraints on the range and lower limit as well.

To avoid difficulties, we normalize our Population II PISN rates from extrapolating observations of GRBs, which are used as tracers of early star formation (Robertson & Ellis 2012).

The expected number of PISNe between redshifts $z$ and $z + \Delta z$ can be calculated by integrating their rate to get

$$N_{\text{PISN}} = \Omega T \int_{z}^{z + \Delta z} \Phi_{\text{PISN}}(z) \frac{dV}{dz} dz,$$

where $\Omega$ is the survey area, $T$ is the survey time, and $dV/dz$ is the differential comoving volume (e.g., Regős & Vinkó 2019).
Note that this gives the number of new events within the survey area during the survey time, but does not take into account cadence or any other observational details that may affect the detection efficiency. With all these other factors included, the number of actual detections will be lower. We will consider the effect of cadence and sensitivity in Section 4.6.

4.5. The Expected Number of PISNe

The expected number of PISNe within the FLARE survey field during the survey time are plotted in Figure 7, where the red dotted curve shows the expected number of Population II PISNe as a function of redshift, while the blue curve is the same but for Population III PISNe.

It is seen that a few Population II PISNe can be expected to occur per unit redshift even within the small ($\sim$300 arcmin$^2$) FLARE survey field during the 3 yr long survey. This is not the case for Population III PISNe, however, as their expected numbers are below 1 in the whole redshift range.

Recently, similar numbers were found by Regős & Vinkó (2019) for the expected counts of superluminous supernovae (SLSNe) during the FLARE survey. Even having the preference of the metal-poor environment of SLSNe taken into account, they were able to predict only a few SLSNe in the FLARE FoV during the 3 yr survey time. Considering that the expected progenitors of PISNe and SLSNe are thought to be very massive stars with a similar mass range, our result above for PISNe is in accord with the prediction of Regős & Vinkó (2019).

Integrating the Population II PISN rate (the red curve in Figure 7) over redshift gives the total number of such PISNe as $N \sim 30$ within the survey field during 3 yr. We use this number to estimate the number of actually detected PISNe during the survey in the next section.

4.6. Simulation

Following Regős & Vinkó (2019), we simulate the FLARE survey observations with JWST by utilizing the sncosmo$^4$ code (Barbary et al. 2016). We draw random samples of $2 \times 30 = 60$ PISNe with explosion times distributed uniformly between $[-1000:1000]$ days with respect to the starting date of the survey, $t_{\text{start}} = 0$ day (the simulation is started 1000 days before $t_{\text{start}}$ in order to take into account those events that are already present in the observed field after the initiation of the survey).

We use 90 day cadence during the 3 yr long survey in the observer’s frame, and sample the light curves from the time-evolving SEDs of the various PISN models with the four selected NIRCam filters (see Section 3) using sncosmo. We assume that the redshift distribution follows the one for the Population II events as shown in Figure 7.

First, we consider the zero metallicity models (see Section 3) having 200, 225, and 250 $M_\odot$ masses. Because the $z > 6$ events are not expected to reach the detection limit of 27.3 AB-magnitude of the FLARE survey, we place them at closer distances and assume the same redshift distribution for them as that of the Population II events. For simplicity, in a random realization of the simulation we use the same mass for all 60 simulated PISNe, and consider the models for the other masses in different simulations. In order to take into account the possible model dependence of the peak brightness, a Gaussian random variable with 1 mag FWHM is added to the peak magnitude of each random event in the simulation.

In each simulation we use the same “strong” and “weak” detection criteria as defined by Regős & Vinkó (2019): “strong” means simultaneous detection in all four NIRCam bands, while “weak” means detection in at least two bands.

Since the random distribution of $\sim$60 SNe may suffer from biases due to low number statistics, we computed 10 different realizations of the 60 randomly distributed PISNe from the same models, and the final redshift distribution of the events that passed the detection criteria (see below) are estimated as the mean values from these 10 different random samples.

Figure 8 displays the statistics of the simulations for the zero metallicity models. “Strong” detections are shown in the upper row, where the three subpanels correspond to the 200, 225, and 250 $M_\odot$ masses, respectively, while the “weak” detections are in the lower row. As visible, detection in all four NIRCam filters is not expected beyond $z \sim 4$ according to these PISN models. Two-band detections are less restrictive, so they might occur up to $z \sim 5$, but not beyond that.

Second, we use the Population II metallicity PISN model having 250 $M_\odot$ mass by Chatzopoulos et al. (2019) in 10 different random realizations of the same simulation as described above (again, assuming for simplicity that all PISNe

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$^4$ https://sncosmo.readthedocs.io/en/v2.0.x/
have the same mass). Because the peak absolute magnitudes of these models (∼−20 AB mag) are ∼3 mag brighter than that of the zero metallicity models, such PISNe could be detected at larger distances, and thus at higher redshifts. Figure 9 displays the number of “weak” detections in the four NIRCam bands. As expected, these numbers are somewhat higher than those presented in Figure 8, but the region of detectability does not extend significantly beyond z ∼ 5. Since the “strong” detection is mostly constrained by the F150W filter (see Figure 3), the redshift distribution of the “strong” detections would look the same as the upper left panel of Figure 8 for all bands. Figure 10 shows the efficiency of the “strong” detections. It is seen that for z < 3 it is practically 100%, i.e., all PISNe are expected to be detectable in all four bands. However, it quickly decreases beyond z ∼ 4, and reaches practically zero around z ∼ 5, meaning that these kinds of PISNe at such redshifts could be detected only in the longer wavelength bands.

Finally, we estimate the likely number of detected PISNe with different masses and metallicities (assuming 100% discovery efficiency) simply by averaging the numbers from the four sets of simulations shown above. Table 1 contains these numbers as a function of redshift, which can be considered our prediction for the PISN outcome of the JWST FLARE survey. (The z = 1 row includes PISN in the range z = 0–1, and weak detections include the strong detections.)

5. Discussion

Even though the numbers in Figures 7–9 suggest that a few PISNe per redshift bin could be discovered with JWST/NIRCam, there are several caveats that should be kept in mind.

Our estimates for the redshift distribution of the expected number of PISNe are based our current understanding of the (redshift-dependent) SFR and initial mass function. (see Section 4.1). At high redshifts these are poorly constrained and may suffer from higher uncertainties.

Also, we know a priori neither the mass nor the metallicity of any real PISN, provided they indeed occur at higher redshifts. Therefore, even though we combined several different models for such events, it is uncertain whether the real PISNe would be similar to these models or not.

As is seen in Figure 7, there seems to be little chance to detect any Population III events with JWST, at least with the conditions of the planned FLARE survey, because their expected numbers do not reach 1 in any redshift bin. On the contrary, Population II events seem to be more numerous, so the discovery of such PISNe is more probable.

The light-curve plots in Figures 1–2 and A1–A2 suggest that the observer’s frame evolution of such events will be slow, on the timescale of several hundred days, as it is stretched by a factor of 1 + z due to time dilation. Thus, if such a transient pops up within the FoV, it will likely remain visible during the
whole survey. However, the classification of these new events will require “strong” detections, i.e., detectability in all four NIRCam filters. The predicted number of such PISNe (Table 1) is only a few per redshift bin, and these numbers are based on assuming 100% discovery efficiency. In reality, it is unlikely that the survey will be able to catch all such events that occur within the FoV. Nevertheless, since the total number of “strong” detections is \( \sim 15 \), even assuming a rather low, 10% discovery efficiency would mean that at least 1–2 PISNe might be found with JWST.

The simulations presented in Section 4.6 highlight that the number of “strong” detections is not expected to be significant for events beyond \( z \sim 4 \) redshift. Because the proposed photometric classification of such objects is based on the color–color diagram (Section 3.3), this constraint also limits the number of potential discoveries. On the other hand, the proposed 90 day observing cadence of the FLARE survey does not seem to be a strong limitation, as PISNe at \( z > 1 \) are slowly evolving, as mentioned above.

Finally, our proposed observational prescription for the discovery of PISNe can be summarized as follows: find a new source within the FoV that is

1. detected in all four bands,
2. has the expected brightness and color, according to Figures 3 and 5, and
3. Remains detectable with NIRCam for more than 1 yr.

Such a transient source could be either an SLSN or a PISN.

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**Table 1**

The Predicted Number of PISN Discoveries in the FLARE Survey

| \( z \) | \( N_{\text{strong}} \) | \( N_{\text{weak}} \) |
|---|---|---|
| 1 | 6(\( \pm 2 \)) | 8(\( \pm 1 \)) |
| 2 | 5(\( \pm 3 \)) | 10(\( \pm 3 \)) |
| 3 | 3(\( \pm 3 \)) | 6(\( \pm 4 \)) |
| 4 | 1(\( \pm 1 \)) | 4(\( \pm 3 \)) |
| 5 | 0(\( \pm 1 \)) | 1(\( \pm 1 \)) |

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**Figure 9.** Number of “weak” detections in the FLARE survey simulation, using the 250 \( M_\odot \) model of Chatzopoulos et al. (2019), as a function of redshift in different filters. Different colors represent 10 random realizations of the simulation.

**Figure 10.** Percentage of strong detections in the FLARE survey simulation as a function of redshift.
6. Conclusion

In spite of their importance to the early universe, not much is known about the properties of Population III stars, as not even JWST or 30–40 m class telescopes or the ELT will be able to see them (Rydberg et al. 2010). Recent discovery of stars above 150 $M_\odot$ in the star cluster R136 (Crowther et al. 2010) and detection of PISN candidates SN 2007bi at $z = 0.123$ (Gal-Yam et al. 2009) and SN 2213-1745 at redshift $z = 2.05$ (Cooke et al. 2012) have excited interest in this exotic explosion mechanism and challenged current theories. Pair instability supernovae, pulsating PISN will be visible to JWST and ELTs at $z > 20$. Rotating PISN will be visible out to $z \sim 10$.

In this paper we considered pair instability supernovae (PISNe), having both Population II (subsolar) and Population III (near-zero) metallicity, and examined whether such events could be detected with the planned FLARE survey with JWST/NIRCam (Wang et al. 2017). Synthetic magnitudes and colors were derived from various PISN models, including the ones published recently by Chatzopoulos et al. (2019) as well as new calculations shown in this paper. The PISN rates and their expected numbers within the FLARE field of view are inferred in a similar way as in Regős & Vinkó (2019) for SLSNe.

It is found that PopII PISNe having $M > 200 M_\odot$ seem to be detectable with JWST/NIRCam down to 27 AB-mag below $z < 4$. Their expected numbers vary between 1 and 10 per unit redshift within $0 < z < 5$ (Figures 7–9). However, current models of Population III PISNe predict too faint peak magnitudes to be detectable with JWST/NIRCam with the proposed observational conditions. Thus, they are more likely to escape detection. The probability of their detection is also decreased by their expected numbers during a 3 yr long survey, which turned out to be below 1 (Figure 7).

It is emphasized that all these conclusions are based on state-of-the-art models of our current understanding of PISN explosions. It is also possible that real PISNe, if they exist, are much brighter than these models predict. If this were the case, then the detection of even one such event would be a breakthrough in understanding star formation and stellar evolution in the early universe.

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Appendix

Models of Population III stellar evolution predict that metal-free stars must have initial masses of 140–260 $M_\odot$ for PISN (Heger & Woosley 2002; although Chatzopoulos & Wheeler 2012a extended the lower mass limit to 85 $M_\odot$ if the star rotates). Figures A1 and A2 show additional light curves of the zero metallicity Population III PISN models in the various NIRCAM bandpasses for 175, 225, and 250 $M_\odot$ progenitors.

Figure A1. Same as Figure 1’s upper panel but for the 175 $M_\odot$ model.
Figure A2. Same as Figure A1 but for the 225 (top panel) and 250 $M_{\odot}$ (bottom panel) models.
