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Pair-instability and super-luminous supernova discoveries at $z = 2.05$, $z = 2.50$, and $z = 3.90$

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Abstract.
We present the discovery of three super-luminous supernovae (SLSNe) at $z = 2-4$ as part of our survey to detect ultraviolet-luminous supernova at $z > 2$. SLSNe are $\geq$10 times more luminous than normal supernova types, reaching peak luminosities of $\gtrsim 10^{44}$ erg s^{-1}. A small subset of SLSNe (type SLSN-R) exhibit a slow evolution, and thus enormous integrated energies ($\gtrsim 10^{51}$ erg), consistent with the radiative decay of several solar masses of ^{56}Ni. SLSN-R are believed to be the deaths of very massive stars, $\sim$140 - 260 M$_\odot$, that are theorized to result in pair-instability supernovae. Two of the high redshift SLSNe presented here are consistent with the behavior of SLSN-R out to the extent in which their light curves are sampled, with the third event being consistent with the more rapid fade of the type II-L SLSN SN 2008es at $z = 0.205$. SLSNe are extremely rare locally but are expected to have been more common in the early Universe and as members of the first generation of stars to form after the Big Bang, the Population III stars. The high intrinsic luminosity of SLSNe and their detectability using our image-stacking technique out to $z \sim 6$ provide the first viable route to detect and study the deaths of massive Population III stars which are expected to form in pristine gas at redshifts as low as $z \sim 2$.

Keywords: core-collapse supernovae, pair-instability supernovae, high-redshift supernovae, population III stars, super-luminous supernovae
PACS: 95, 98

INTRODUCTION

Super-luminous supernovae (SLSNe) have recently been classified into three groups [1]: SLSN-I that show no hydrogen, SLSN-II that are hydrogen rich and include a subset that exhibit emission from circumstellar interaction, and SLSN-R that exhibit a slow light curve evolution consistent with the radiative decay of several solar masses of ^{56}Ni. As a result of the recent discovery of SLSNe in large-area, supernova searches in the last decade and their extreme rarity, the mechanisms behind the enormous energy production of SLSN are poorly understood. The exception is the subtype SLSN-R which are believed to be pair-instability supernovae. Although the pair-instability process has been well-understood for decades [2, 3], SLSN-R are an order of magnitude more

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rare than SLSN-I or SLSN-II [1]. SN 2007bi at $z = 0.128$ [4] is perhaps the only observational example a bona-fide SLSN-R measured out to late times, with a few other candidates currently being followed. Finally, only the progenitor masses of SLSN-R are well-constrained (140 - 260 $M_\odot$ [5]), however from energy and mass loss considerations it is likely that all SLSNe require > 30 $M_\odot$ progenitors.

Previously, SLSN and core-collapse supernova have only been detected to $z \lesssim 0.9$. Modification of our image-stacking high redshift supernova detection technique [6] has uncovered three $z > 2$ SLSNe to date. The unique far-ultraviolet (FUV) data from these events is key toward progressing stellar evolutionary models and their estimated rate may provide the first direct evidence confirming the expectation that the number of massive stars at high redshift is greater than at low redshift. Finally, the enormous FUV and expected high density of SLSNe at high redshift indicates that they may have provided an important contribution of ionizing photons to the early Universe.

Relevant to this meeting are the Population III stars which have a mass distribution that is expected to have been skewed to very high masses [7, 8]. Regions of pristine gas able to host late-forming Population III stars are theorized to exist down to $z \sim 2$ [9, 10, 11] and the discovery of clouds of pristine gas at $z \sim 3$ in absorption to more distant quasars [12] provides strong support. As a result of their extreme luminosity, SLSNe can be detected at $z \sim 2-6$ in existing and upcoming surveys such as the HyperSuprime-Cam Deep and Ultradeep surveys. Because this redshift range significantly overlaps with the regime of the first stars, SLSN detections using our technique offer the first viable route to observe massive Population III star deaths.

OBSERVATIONS

The three high redshift SLSNe were discovered in the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) Deep field archival data. Our technique searches for supernovae in stacked images that combine data from $\sim$25 – 30 nights, acquired over $\sim$6-month observing seasons, per year during 2003 – 2008. Figure 1 presents the supernova light curves generated from the nightly-stacked images during the detection years.

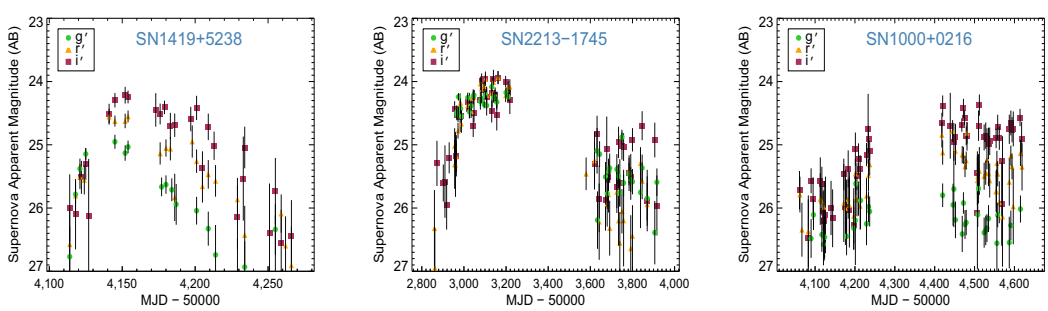

FIGURE 1. Observed g'r'i' light curves for high redshift super-luminous supernovae. **Left:** The quickly evolving SN1419+5238 at $z = 2.49$ discovered in CFHTLS Deep field 'D3'. **Center:** The slowly evolving SN2213-1745 at $z = 2.05$ discovered in field 'D4'. **Right:** SN1000+0216 at $z = 3.90$ discovered in field 'D2'. The gaps in coverage in the center and right panels are the $\sim$6 months when the fields were not observable. The g'r'i' filters correspond to restframe far-ultraviolet wavelengths $\sim$1000 - 2000Å.

Follow-up spectroscopy of the supernovae and host galaxies was acquired $3.8-5.2$ years, observed frame, after first detection using the Low-Resolution Imaging Spectrograph on the 10-m Keck I telescope and confirms redshifts $z = 2.05$ for SN2213-1745, $z = 2.49$ for SN1419+5238, and $z = 3.90$ for SN 1000+0216. The deep spectroscopy also provides global host galaxy FUV properties and can detect the presence of long-lived supernova emission features as a result of circumstellar interaction [13, 14, 15]. None of the spectra exhibit signs of AGN activity such as Lyα with N V and C IV emission.

RESULTS

The CFHTLS images are sensitive to a rise to peak and fade of $\sim 2-3$ mag for SLSNe at $z \sim 2-4$. Because SLSNe-I and most SLSNe-II typically rise and fade over $\sim 1.5-2$ months, restframe, they are detected in one $\sim$6 month, observed-frame, seasonal-stacked image and fade sufficiently to evade detection in the subsequent season. SN1419+5238 is detected in only one season and is seen to closely follow the linear evolution of the *Swift* satellite FUV light curves of SLSN-II SN 2008es ($z = 0.205$ [16]) that probe similar restframe wavelengths as our data (Figure 2). However, the presence of hydrogen and a SLSN-II classification cannot be confirmed from the late-time spectrum.

In contrast, the enormous flux ($\gtrsim 10^{51}$ erg) generated by SLSNe-R can straddle two, or even three $\sim$6-month seasons depending on redshift. The light curves of SN2213-1745 (Figure 2) span two seasons and are found to be in close agreement with the energy and evolution of the low redshift SLSN-R SN 2007bi. SN1000+0216 (Figure

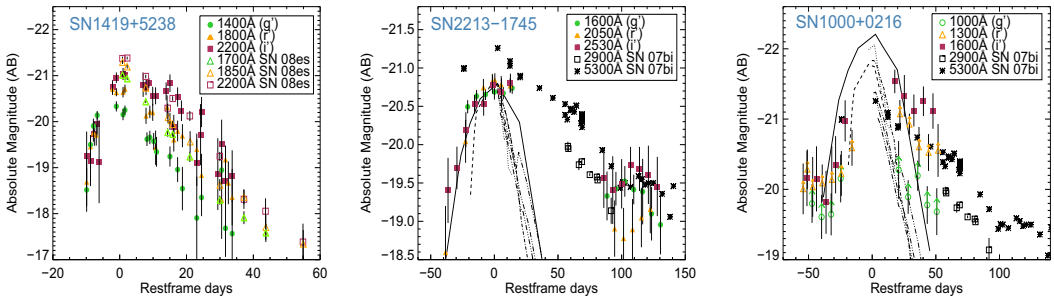

FIGURE 2. Comparison of super-luminous supernova absolute magnitude light curves. **Left:** SN1419+5238 *(filled symbols)* exhibits similar behavior to the *Swift* FUV data of low-redshift SLSN-II SN 2008es [16] classified as a type II-L *(empty symbols)*. **Center:** SN2213-1745 *(filled symbols; 7 day binning restframe)* is compared to near- and far-ultraviolet data for known SLSNe: SLSN-I SCP 06F6 *($\sim$3500Å, solid curve [17])*, SLSN-I SN 2008gx *($\sim$2900Å, dotted curve [18])*, SLSN-I PS1-10awh *($\sim$2500Å, dashed curve [19])*, SLSN-I PS1-10ky *($\sim$2500Å, dot-dashed curve [19])*, and SLSN-II SN 2008es *($\sim$1700-2200Å, dot-dot-dashed curves)*. Also shown are near-ultraviolet and optical data for SLSN-R SN 2007bi [20, 4] *(see legend)*. The SLSN-I and SLSN-II data have $\sim$0-1.5 mag offsets applied to match the estimated peak of SN2213-1745 for evolution comparison (SN 2007bi data has no offset). All SLSNe exhibit much quicker evolution as compared to SN2213-1745, except SLSN-R SN 2007bi which is similar. **Right:** Same as the center panel but for SN1000+0216. Here, the low-redshift SLSNe are not offset to match the estimated peak in our data and the SN 2007bi data remain unshifted. We assume the peak mag for SN1000+0216 occurs between detection seasons 1 and 2.

2) appears to also evolve slowly, but because of its higher redshift, the photometry spans a shorter amount of time than SN2213-1745 (the CFHTLS survey ended in 2008) and the g' and r' filters are strongly affected by the Lyα forest. Because the full evolution of SN1000+0216 remains unclear and the implied enormous energy may exceed SLSN-R model expectations, its subtype remains unknown.

The three events occurring in the well-defined volumes probed by our high redshift galaxy selection method [6, 15] produce a rough SLSN volumetric rate of $\sim 4-8\times 10^{-7}h_{71}^{3}$ Mpc^3 yr^{-1} ($H_0 = 71$, $\Omega_0 = 0.27$, $\Omega_\Lambda = 0.73$), when convolved with the survey window function. This rate is to be compared with $\sim 10^{-8}h_{71}^{3}$ Mpc^3 yr^{-1} for SLSNe at low redshift [21]. After correcting for a factor of $\sim$5 increase expected as a result of the increase in the cosmic star formation rate from $z \sim 0.3$ to $z \sim 2-4$, we find that our rough high redshift SLSN rate appears to be $\sim$10$\times$ higher than that at low redshift.

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