Superluminous supernovae at redshifts of 2.05 and 3.90

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A rare class of ‘superluminous’ supernovae that are about ten or more times more luminous at their peaks than other types of luminous supernova has recently been found at low to intermediate redshifts1–2. A small subset of these events have luminosities that evolve slowly and result in radiated energies of up to about $10^{51}$ ergs. Therefore, they are probably examples of ‘pair-instability’ or ‘pulsational pair-instability’ supernovae with estimated progenitor masses of 100 to 250 times that of the Sun3–5. These events are exceedingly rare at low redshift, but are expected to be more common at high redshift because the mass distribution of the earliest stars was probably skewed to high values6–8. Here we report the detection of two superluminous supernovae, at redshifts of 2.05 and 3.90, that have slowly evolving light curves. We estimate the rate of events at redshifts of 2 and 4 to be approximately ten times higher than the rate at low redshift. The extreme luminosities of superluminous supernovae extend the redshift limit for supernova detection using present technology, previously 2.36 (ref. 8), and provide a way of investigating the deaths of the first generation of stars to form after the Big Bang.

We search for high-redshift superluminous supernovae (SLSNe) by modifying our image stacking and analysis technique9 to their expected light-curve evolution and high luminosities as recently determined from theory and low-redshift observations. Supernovae SN 2213-1745 and SN 1000+0216 were discovered when applying our modified technique to the Canada-France-Hawaii Telescope Legacy Survey Deep Fields. These archival survey data provide deep, consistent photometry of the host galaxies over ~6-month seasons from 2003 to 2008 and allow accurate extraction of the supernova-rest-frame far-ultraviolet light. Follow-up late-time spectroscopy of the supernovae and their host galaxies was obtained using the 10-m Keck I telescope 5.2 and 3.8 yr (~626 and ~286 d, rest frame) after first detection for SN 2213-1745 and SN 1000+0216, respectively. The deep Keck data reveal redshifts of $z = 2.0458$ for SN 2213-1745 and $z = 3.8993$ for SN 1000+0216. Details of the supernovae and their host galaxies are listed in Table 1.

SN 2213-1745 is detected in the 2005 and 2006 seasonal (June–November) stacked images for deep field D4, and SN 1000+0216 is detected in the 2006–2007 and 2007–2008 seasonal (November–June) stacked images for deep field D2 (Fig. 1). Neither supernova is detected in the previous two seasons above the stacked-image detection limit of $m \approx 26.5$ mag (Supplementary Information, section A). The nightly images that comprise the seasonal stacks first show the supernovae at the onset of the observing seasons. The lack of detection in previous seasons implies that the initial outbursts occurred between November 2004 and June 2005 for SN 2213-1745 and between June and November 2006 for SN 1000+0216. Both supernovae evolve slowly and reach high peak luminosities of $\sim 0.5 \times 10^{44}$ to $1 \times 10^{44}$ erg s$^{-1}$, uncorrected for host galaxy extinction. The peak luminosities correspond to far-ultraviolet absolute AB magnitudes10,11 of $M_{\nu,\text{peak}} \approx -21$ mag and thereby rule out all normal supernova subtypes. SLSNe are the only supernova type that can generate similar peak magnitudes and light-curve evolution (Fig. 2).

Although active galactic nuclei (AGNs), powered by the erratic accretion of material onto supermassive black holes at the centres of galaxies, can produce similar energies, both host galaxies exhibit a single supernova-like outburst, present no activity during the previous two years and have colours that are inconsistent with high-redshift AGNs, including the eight spectroscopic AGNs in our sample. Moreover, the SN 2213-1745 host spectrum does not show signs of AGN activity (Fig. 3), and although the SN 1000+0216 host spectrum shows narrow Lyα emission, common to high-redshift galaxies, no other AGN-associated features are seen. In contrast, the images reveal zero, or very small, separations (projected in the plane of the sky) from their host galaxy centroids (Supplementary Information, section A). We note that our technique is limited to detecting supernovae within the small extent of the high-redshift host galaxies that produces far-ultraviolet flux, and that far-ultraviolet light directly traces regions of high star formation and does not necessarily provide accurate galaxy centroids. Finally, although the ultraviolet–optical afterglows of long-duration γ-ray bursts can achieve luminosities equivalent to, or greater than, the observed events, the bursts typically reach their peak luminosities within a day and quickly decay12, usually in inverse proportion to time. This behaviour is inconsistent with the observed slow rise and slow decay of the events discussed here.

Recently, SLSNe have been classified into groups on the basis of their photometric and spectroscopic properties2. Those in group SLSN-I show no evidence of hydrogen in their spectra, whereas those

| Supernova | Host M_{FUV} (mag) | Supernova peak M_{FUV} (mag) | Detection dates | Redshift |
|-----------|--------------------|-----------------------------|----------------|---------|
| SN 2213-1745 | 21.2 | $-17.45^\circ 24.486^\prime$ | $-21.38 \pm 0.03$ | $-21.2 \pm 0.2$ | June 2005–November 2006 |
| SN 1000+0216 | 21.0 | $+02.16^\circ 23.621^\prime$ | $-21.20 \pm 0.04$ | $-21.5 \pm 0.2$ | November 2006–June 2008 |

1The far-ultraviolet absolute magnitudes, $M_{\nu,\text{peak}}$, are derived using the conventional relationship $M_{\nu,\text{peak}} = m_{\nu} - 5 \log_{10}(D/L) + 25 \log_{10}(1+z)$, where $m_{\nu}$ is the observed redshifted far-ultraviolet AB magnitude10,11 and $D_L$ is the luminosity distance, adopting a standard cosmology with Hubble parameter $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, mass density $\Omega_m = 0.73$ and vacuum energy density $\Omega_{\Lambda} = 0.27$. The supernova absolute magnitudes are corrected for extinction by the Milky Way10 (0.04–0.11 mag) but not corrected for supernova host galaxy extinction.

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Figure 1 | Light curves of high-redshift supernovae. Plotted as functions of time (MJD, modified Julian date) are the observed supernova $g'$-, $r'$- and $i'$-band magnitudes and $1\sigma$ errors detected in nightly stacked images after host galaxy flux subtraction. The high-quality images used in our study provide consistent and accurate photometry of the supernova host galaxies for $\sim6$ months per year for four years (Supplementary Information, section A). a, Magnitudes for SN 2213-1745 ($z = 2.05$) detected in deep field D4 during the observing seasons June–November 2005 and June–November 2006. The optical $g'$-, $r'$- and $i'$-band data correspond to rest-frame far-ultraviolet continuum wavelengths of $\sim1,600, \sim2,050$ and $\sim2,530\,\text{Å}$, respectively. b, Magnitudes for SN 1000+0216 ($z = 3.90$) detected in deep field D2 during the observing seasons November 2006–June 2007 and November 2007–June 2008. Here, the $g'$-, $r'$- and $i'$-band filters correspond to rest-frame wavelengths of $\sim1,000, \sim1,300$ and $\sim1,600\,\text{Å}$, respectively. As a result, only the $i'$ filter samples the far-ultraviolet continuum exclusively. The $r'$ filter probes the continuum and the Lyman-$\alpha$ (Ly$\alpha$) feature and samples the decrement in flux on the short-wavelength side of the Ly$\alpha$ feature caused by optically thick systems at lower redshifts. The $g'$ filter completely samples the spectral region of the Ly$\alpha$ forest to just below the Lyman limit.

in group SLSN-II are rich in hydrogen and include a subset showing signs of interaction with circumstellar material. Finally, those in group SLSN-R have light curves that evolve slowly, powered by the radiative decay of $^{56}\text{Ni}$. SLSN-R events are suspected to be pair-instability supernovae: the deaths of stars with initial masses between 140 and 260 solar masses$^{3,5}$. The physics of the pair-instability process has been understood for many years, but the extreme rarity of SLSNe-R ($\sim10$ times less frequent than SLSNe-I or SLSNe-II) has resulted in only one believable recorded event, SN 2007bi$^{14}$, which is well studied up to late times, with a few candidates being followed by ongoing low-redshift surveys.

In Fig. 2, we compare the photometric evolution of the high-redshift supernovae with lower-redshift SLSN data at similar wavelengths$^{14-18}$. All SLSNe, except for SLSN-R SN 2007bi, which is estimated to be powered by about four to seven solar masses of $^{56}\text{Ni}$, fade significantly quicker than the two high-redshift events. As far as can be determined from the photometry, the evolution of SN 2213-1745 is consistent with SN 2007bi and, as a result, provides the first far-ultraviolet data for an
Figure 3 | Late-time spectra of the supernovae and host galaxies. The spectra are shown as the dark-grey filled regions. Although Lyman-break galaxies are extremely distant, they have strong absorption features and a prominent Lyα feature at 1,216 Å, seen in absorption and/or emission, which enable reliable identification. Labelled vertical dashed lines indicate typical atomic transitions seen in absorption. Additional absorption features may be present as a result of lower-redshift systems in the line of sight. Thick vertical light-grey lines mark the positions of bright night-sky emission lines that are difficult to remove cleanly from faint spectra. a. Spectrum of SN 2213-1745 obtained 626 days (rest frame) after first detection, plotted as in a. The poorer observing conditions and fainter nature of this object resulted in a spectrum with a lower signal-to-noise ratio and in more difficulty subtracting bright night-sky lines. However, a confident host galaxy identification and redshift determination is achieved in part on the basis of the significant narrow Lyα emission and the decrement in continuum flux at short wavelengths relative to Lyα as a result of the Lyα forest. Although the host galaxy exhibits narrow Lyα emission (observed in >50% of Lyman-break galaxies), associated AGN features, such as N 5 1,240 Å and C IV 1,550 Å, are not seen at any significance. Flux correction between 6,300 and 6,800 Å is underrepresented and less reliable (Supplementary Information, section A).

SLSN-R. The close agreement suggests that SN 2213-1745 may be powered by the radiative decay of a similar amount of synthesized 56Ni, and, along with an integrated radiated luminosity of ~10^41 erg, implies a progenitor with an estimated initial mass of about 250 solar masses. We note that although SN 2213-1745 is shown to follow closely the luminosity evolution of a radiation-hydrodynamics SLSN-R simulation19 for a progenitor star of similar mass, the observed flux is higher and bluer than the model expectations (Supplementary Information, section C).

SN 1000+0216 was observed over a shorter time period than was SN 2213-1745, as a result of time dilation. The range of the light curve sampled suggests a longer rise time than SN 2213-1745 but seems to follow a similar fade rate from peak luminosity to ~50 d later (rest frame), if we assume that the peak occurred during the gap in coverage between the two detection seasons. The peak far-ultraviolet magnitude of SN 1000+0216 may exceed that possible for a pair-instability supernova. As a result, SN 1000+0216 may be an example of a pulsational pair-instability supernova2 or a SLSN-II similar to the low-redshift SN 2006gy20,21, which experience enhanced luminosity as a result of interaction with previously expelled circumstellar material (Supplementary Information, sections D and F). The high luminosity of SN 1000+0216 classifies it as an SLSN but, because of its limited photometric coverage and low signal-to-noise host spectrum, its subclassification remains uncertain.

Our programme searches for z ≥ 2 supernovae by monitoring the well-studied population of Lyman-break galaxies22–24 over several well-defined volumes. Because Lyman-break galaxies comprise the bulk of galaxies at high redshift, where star formation rates are higher, normal populations of short-lived, massive stars are more common at z ≥ 2 than locally. From the specifics of our survey, the two SLSN detections imply a rough volumetric high-redshift rate of ~4 × 10^{-7} h_{70}^{-3} Mpc^{-3} yr^{-1} (where h_{70} is the dimensionless Hubble parameter) at z = 2.2 ± 0.3 and z = 4.1 ± 0.3 (mean ± 1σ) (Supplementary Information, section B). After correcting for the increase in the cosmic star formation rate from low to high redshift, the SLSN rate remains ~10 times higher than that estimated at low redshift2, but we caution that our rate estimate is poorly constrained because it is derived from only two events. The far-ultraviolet photometry confirms that the two supernovae are strong sources of escaping high-energy photons. However, far-ultraviolet light is highly susceptible to metal-line absorption and local and global dust extinction that may have a greater effect on other high-redshift SLSNe and cause them to fall below our detection threshold. A result, our estimated rate is a lower limit and implies that the discrepancy between low and high redshift may be even greater.
The detection of SLSNe at z > 2 presents the possibility of finding the explosions of population III stars, the first stars to form after the Big Bang. Population III stars are predicted to exist at redshifts as low as z = 2 (refs 25–28) and have mass distributions skewed towards high masses. On the basis of our late-time spectroscopy, the supernovae presented here are unlikely to be from the first generation of stars (Supplementary Information, section E). Deep spectroscopy of future supernovae obtained near maximum brightness, and their use as sightline probes, offers a means to help distinguish which events formed in regions with essentially no enrichment in elements heavier than helium, and thus probably had population III progenitors.

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Author Contributions J.C. developed the detection technique and the modification for SLSNe; analysed the imaging data and performed the supernova selection; and obtained, reduced and analysed the spectroscopic observations. M.S. was responsible for the reduction and analysis of the seasonal image stacks, supernova flux extraction and supernova candidate light curves. A.G.Y. provided supernova analysis and manuscript contributions and advice. E.J.B. performed observations and provided observing time and scientific discussions. R.G.C. provided manuscript advice, was one of the proponents of the CFHT Legacy Survey and, as the Canadian Principal Investigator, assembled the team responsible for much of the operation and analysis of the legacy survey. E.V.R.-W. enabled spectroscopic observations and provided discussions and student support. C.H. performed Keck spectroscopic observations and data reduction. Y.O. and C.G.D. performed Keck spectroscopic observations.

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