LETTER

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Hydrogen-poor superluminous stellar explosions

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Supernovae are stellar explosions driven by gravitational or thermonuclear energy that is observed as electromagnetic radiation emitted over weeks or more[1]. In all known supernovae, this radiation comes from internal energy deposited in the outflowing ejecta by one or more of the following processes: radioactive decay of freshly synthesized elements[2] (typically ^{56}Ni), the explosion shock in the envelope of a supergiant star[3], and interaction between the debris and slowly moving, hydrogen-rich circumstellar material[4]. Here we report observations of a class of luminous supernovae whose properties cannot be explained by any of these processes. The class includes four new supernovae that we have discovered and two previously unexplained events[5,6] (SN 2005ap and SCP 06F6) that we can now identify as members of the same class. These supernovae are all about ten times brighter than most type Ia supernova, do not show any trace of hydrogen, emit significant ultraviolet flux for extended periods of time and have late-time decay rates that are inconsistent with radioactivity. Our data require that the observed radiation be emitted by hydrogen-free material distributed over a large radius ($\sim$10^{15} centimetres) and expanding at high speeds (>10^4 kilometres per second). These long-lived, ultraviolet-luminous events can be observed out to redshifts $z > 4$.

The Palomar Transient Factory[7,8] (PTF) is a project dedicated to finding explosive events and has so far identified over one thousand supernovae. PTF09atu, PTF09cnd and PTF09cwl (also known as SN 2009jh[9]) were detected using the Palomar Observatory's 1.2-m Samuel Oschin Telescope during commissioning of the PTF system, in 2009, and PTF10cwr[10–12] (SN 2010gx[13]) was detected the following year (Fig. 1; see Supplementary Information, section 1). As with other supernova candidates, optical spectra for classification were obtained using the W. M. Keck Observatory's 10-m Keck I telescope, Palomar Observatory's 5.1-m Hale Telescope, and the 4.2-m William Herschel Telescope. The spectra (Fig. 2) show broad absorption dips at short wavelengths and mostly smooth continua at longer wavelengths. We further identify narrow absorption features in the PTF spectra from the Mg II doublet at rest wavelengths 2,796 Å and 2,803 Å, and measure redshifts of $z = 0.501$, 0.258, 0.349 and 0.230 for PTF09atu, PTF09cnd, PTF09cwl and

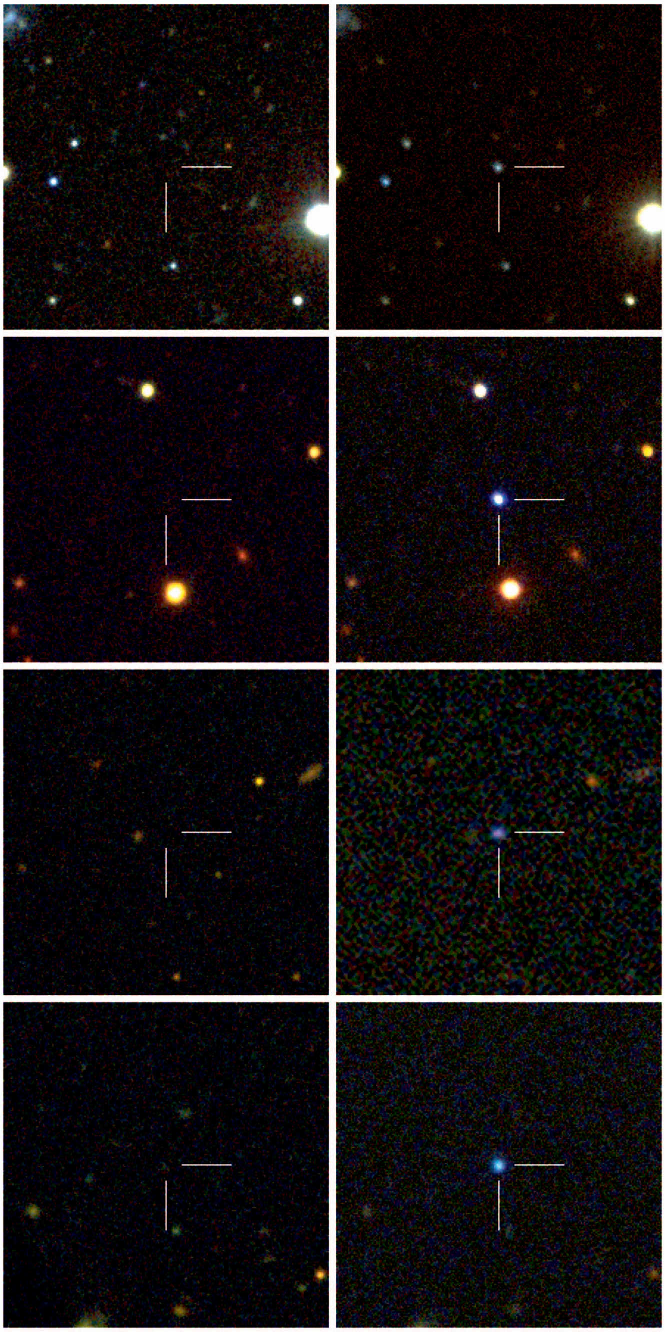

Figure 1 | Ultraviolet-luminous transients discovered by the PTF. Left: before explosion; right: after explosion; top to bottom: PTF09atu, PTF09cnd, PTF09cwl and PTF10cwr. Each tile shows a false-colour image constructed by assigning image data from three separate band passes to red, blue and green (g, r and i bands, respectively, for PTF09atu; u, g or V, and r bands for PTF09cnd, PTF09cwl and PTF10cwr). In each case, Sloan Digital Sky Survey reference data form the pre-explosion image. The post-explosion images are composed from observations made with the Palomar Observatory's 1.5-m telescope, the Wise Observatory's 1.0-m telescope and the Ultraviolet/Optical Telescope on board NASA's Swift satellite.

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PTF10cwr, respectively. After combining the three available spectra of the SCP 06F6 transient, we find that the data correlate to the PTF sample and may also show narrow Mg II absorption with redshift $z = 1.189$ (Supplementary Information, section 4). Similarly to all PTF events, SN 2005ap ($z = 0.283$) shows a distinct W-shaped absorption feature near rest wavelength 4,300 Å. Although the broad spectral features of SN 2005ap are systematically shifted to higher speeds, the overall resemblance to the other PTF events is striking. The PTF discoveries bridge the redshift gap between SCP 06F6 and SN 2005ap and link these once disparate events, thus unifying them all into a single class.

With the redshifts above and a standard flat cosmology with Hubble parameter $H_0 = 71$ and matter energy density $\Omega_m = 0.27$, the peak absolute u-band AB magnitudes[14] for the PTF transients in the rest frame are near −22 mag and that for SCP 06F6 is near −22.3 mag (Fig. 3). The ~50-d rise of SCP 06F6 to maximum in the rest frame is compatible with the PTF sample, although there seems to be some diversity in the rise and decline timescales. To power these high peak magnitudes with radioactivity, several solar masses ($M_\odot$) of ^{56}Ni are needed (>$10M_\odot$, following ref. 15), and yet in the rest frame V band, the post-maximum decline rates of the PTF events are all >0.03 mag d^{-1}, which is a few times higher than the decay rate of ^{56}Co (the long-lived daughter nucleus of ^{56}Ni). These are therefore not radioactively powered events.

Next we check whether the observed photons could have been deposited by the explosion shock as it traversed the progenitor star. The photospheric radius, R_{ph}, that we infer for PTF09cnd at peak luminosity, on the basis of the observed temperature and assuming blackbody emission, is $R_{ph} \approx 5 \times 10^{15}$ cm (Supplementary Fig. 1). If the radiated photons were generated during the star explosion, then adiabatic losses would result in only a fraction R_*/R_{ph} of the energy remaining in the radiation at any given time, where R_* is the initial stellar radius. Given that the energy radiated around the peak is $\sim 10^{51}$ erg and that $R_*/R_{ph} < 10^{-3}$ for virtually any hydrogen-stripped progenitor, this model requires an unrealistic total explosion energy of $>10^{54}$ erg. In fact, the large radius and the duration of PTF09cnd leave almost no place for adiabatic losses (Supplementary Information, section 5), implying that the internal energy must have been deposited at a radius that is not much smaller than R_{ph}.

Integrating the rest frame g-band light curve and assuming no bolometric correction, we find that PTF09cnd radiated $\sim 1.2 \times 10^{51}$ erg. A similar analysis of the SCP 06F6 data gives a radiated energy of $\sim 1.7 \times 10^{51}$ erg. We also fit Planck functions to the ultraviolet and optical observations of PTF09cnd (Supplementary Fig. 1) and find an approximate bolometric output of $\sim 1.7 \times 10^{51}$ erg. The derived blackbody radii indicate a photospheric expansion speed of $v_{ph} \approx 14{,}000$ km s^{-1}. If the main source of luminance were the conversion of kinetic energy, then the bolometric energy would require $\sim 1M_\odot$ of material at this speed, assuming a conversion efficiency of 100%. A more realistic efficiency factor would make the minimum mass a few times larger. Because no traces of hydrogen are seen in any of the spectra (Supplementary Information, section 3), interaction with ordinary hydrogen-rich circumstellar material is ruled out. We thus conclude that these events cannot be powered by any of the commonly invoked processes driving known supernova classes.

The early spectra presented here are dominated by oxygen lines and do not show calcium lines, iron lines or other features commonly seen in ordinary core-collapse supernovae. The lack of metals is particularly noticeable in the ultraviolet flux, which is typically depleted by absorption. These events are hosted by low-luminosity galaxies that may provide a subsolar progenitor environment (Supplementary Information, section 6). The new class of events we have identified is thus observationally characterized by extreme peak luminosities, short decay times inconsistent with radioactivity, and very hot early spectra with significant ultraviolet flux and lacking absorption lines from heavy elements such calcium and iron, which are commonly seen in all other types of supernova.

These observations require a late deposition of a large amount of energy (>10^{51} erg) into hydrogen-poor, rapidly expanding material (slow-moving material would produce narrow spectroscopic features, which are not observed). We point out two possible physical processes that can perhaps power these superluminous sources. One is a strong interaction with a massive, rapidly expanding, hydrogen-free shell.

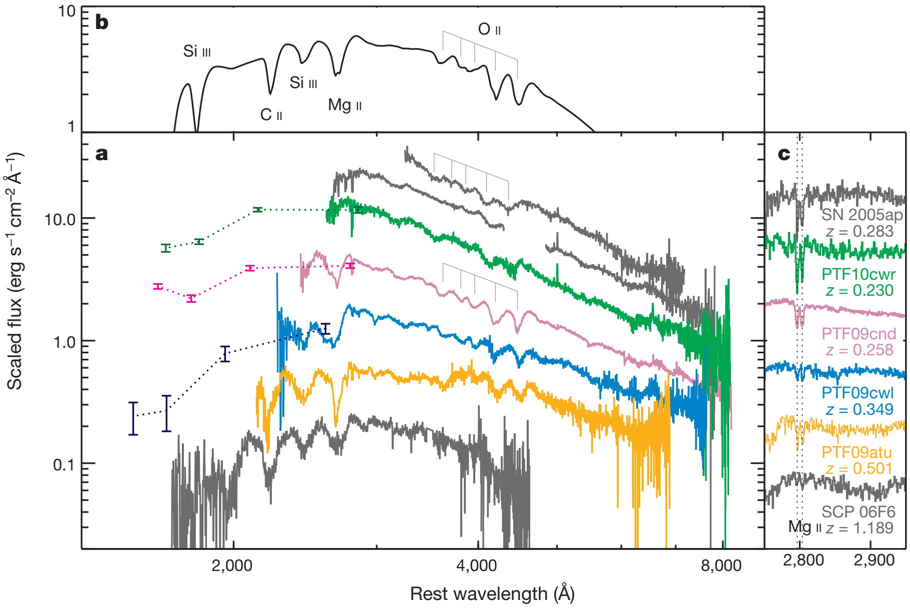

Figure 2 | Spectral energy distributions of the SN 2005ap-like sample. **a**, Top to bottom: SN 2005ap on 2005 March 7 and again on March 16 (grey), PTF10cwr on 2010 March 18 (green), PTF09cnd on 2009 August 25 (purple), PTF09cwl on 2009 August 25 (blue), PTF09atu on 2009 July 20 (orange) and an average of all three SCP 06F6 spectra presented in ref. 6 (grey). The spectra have been adjusted to remove the effect of redshift, binned and scaled arbitrarily for display purposes. Broadband flux densities from the Swift observations (scaled to join the spectra in the u band) are plotted for PTF09cnd, PTF09cwl and PTF10cwr with 1σ error bars. Five absorption bands are marked by the combs above SN 2005ap and PTF09cnd, the former being ~7,000 km s^{-1} faster. **b**, These features can be well fitted by O II using the highly parametric spectral synthesis code SYNOW[21] (Supplementary Information, section 2). SYNOW fits also suggest that C II and Mg II can account for the respective features at 2,200 Å and 2,700 Å. The fit to the line at 2,500 Å is improved with the addition of Si III. The model shown has a photospheric speed of 15,000 km s^{-1}. **c**, Close-up views of the narrow Mg II doublet, from which we derive the redshifts.

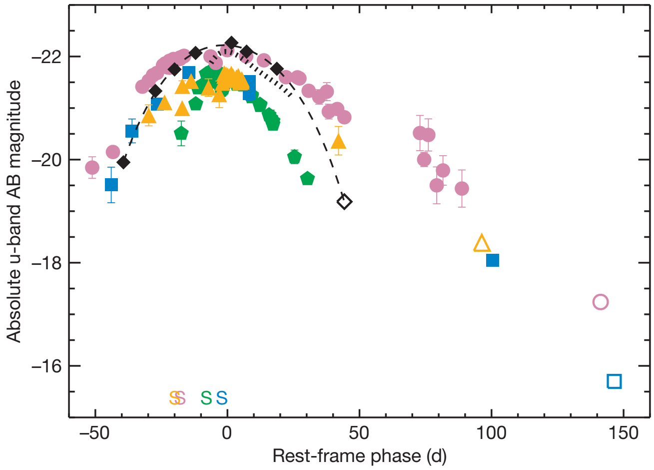

Figure 3 | Luminosity evolution of the SN 2005ap-like sample. Shown are the SCP 06F6 transient (diamonds), SN 2005ap (hatching), PTF09atu (orange triangles), PTF09cnd (purple dots), PTF09cwl (blue squares) and PTF10cwr (green pentagons). In each case, we transform the observed photometry to absolute u-band magnitudes by correcting both for distance and differences in the effective rest-frame band pass introduced by the redshifts. For SCP 06F6, the observed i band is similar to the rest frame u band, so the correction factor is nearly independent of the spectral properties[22]. For the PTF sample, however, the correction factor varies over time as the supernovae cool. We interpolated the observed spectra of PTF09cnd to phases appropriate for the B-, g-, V- and r-band observations of the PTF sample to calculate the correction factors. Errors bars representing 1σ (excluding the colour correction) are shown when larger than the plotting symbols. The colour corrections for PTF09atu and PTF09cwl near day 100 are very uncertain ($\sim$0.5 mag). We have not removed possible host light contaminating the late-time observations of PTF09atu, PTF09cnd and PTF09cwl (open symbols). Thus, these measurements represent upper limits on the supernova light. Host galaxy light may in fact dominate the final PTF09cwl observation. The final observation of SCP 06F6 (open diamond) is a 2.5σ detection made from the ground. Along the abscissa, with appropriately colour-coded 'S's we note the phases of spectra shown in Fig. 2.

Such a situation is naturally produced by extremely massive stars with initial masses in the range 90 $M_\odot \lesssim M_i \lesssim 130\ M_\odot$, which are expected[16,17] to undergo violent pulsations—perhaps driven by the pair instability—that strip their outer layers and expel massive, hydrogen-poor shells. The star eventually dies by becoming a stripped-envelope, core-collapse supernova, which may interact with previously ejected carbon- or oxygen-rich shells to drive the observed luminosity[18]. Alternatively, the power source can be a prolonged energy injection by a central engine. For example, a spinning-down nascent magnetar[19,20] can account for the peak luminosities ($>10^{44}$ erg s^{-1}) and time to peak light (30–50 d) observed for these events, assuming a magnetic field $B \approx (1\text{–}3) \times 10^{14}$ G and a natal spin period of 1–3 ms.

The high luminosities, exceptionally blue spectral energy distributions and volumetric event rates (Supplementary Information, section 7) of this new class of supernovae make them prime targets for high-redshift studies (Supplementary Fig. 3). Because they remain at around maximum luminosity for months to years in the observer frame, these events provide a steady light source to illuminate their environs and any intervening clouds of gas and dust. This creates new opportunities for high-resolution spectroscopy to probe distant star-forming regions in primitive galaxies without the need for rapid scheduling and with the benefit that the luminous supernova beacon eventually fades, allowing the study of the galaxy itself. Indeed, these events promise to be a rich source of results for future 30-m-class-telescope science.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions R.M.Q. initiated, coordinated and managed the project, carried out photometric and spectroscopic observations and analysis, and wrote the manuscript. S.R.K. is the PTF principal investigator and contributed to manuscript preparation. M.M.K. obtained spectroscopy from the Keck I telescope and helped with the P60 observations. A.G.-Y. oversaw the Wise observations and contributed to analysis and manuscript writing. I.A. extracted the Wise photometry and helped obtain Keck I spectra. M.S. carried out and analysed spectroscopic observations from the William Herschel Telescope. P.N. designed and implemented the image-subtraction pipeline that detected the PTF events. R.T. analysed the combined spectra using his automated SYNOW code. D.A.H. helped to identify the PTF spectra as being like that of SN 2005ap. E.N. contributed to the physical interpretation and manuscript writing. L.B. advised during the preparation of the manuscript. C.T. helped vet potential candidates and first identified PTF09atu and PTF09cwl. N.M.L. is the PTF project scientist and oversaw the PTF system. R.D., G.R., D.H., R.S., E.O.O., J.Z., V.V., R.W., J.H., K.B. and D.M. helped to build and commission the PTF system. D.P., S.B.C. and D.L. helped to vet PTF candidates and obtain spectroscopic observations.

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