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A Wolf-Rayet-like progenitor of SN 2013cu from spectral observations of a stellar wind.

A Wolf-Rayet-like progenitor of supernova SN 2013cu from spectral observations of a wind

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The explosive fate of massive stripped Wolf-Rayet (W-R) stars[1] is a key open question in stellar physics. An appealing option is that hydrogen-deficient W-R stars are the progenitors of some H-poor supernova (SN) explosions of Types IIb, Ib, and Ic[2]. A blue object, having luminosity and colors consistent with those of some W-R stars, has been recently identified at the location of a SN Ib in pre-explosion images[3] but has not yet been conclusively determined to have been the progenitor. Similar previous works have so far only resulted in nondetections[4]. Comparison of early photometric observations of Type Ic supernovae with theoretical models suggests that the progenitor stars had radii $< 10^{12}$ cm, as expected for some W-R stars[5]. However, the hallmark signature of W-R stars, their emission-line spectra, cannot be probed by such studies. Here, we report the detection of strong emission lines in an early-time spectrum of SN 2013cu (iPTF13ast; Type IIb) obtained ~ 15.5 hr after explosion ("flash spectroscopy"). We identify W-R-like wind signatures suggesting a progenitor of the WN(h) subclass. The extent of this dense wind may indicate increased mass loss from the progenitor shortly prior to its explosion, consistent with recent theoretical predictions[6].

W-R stars are massive stars stripped of their outer H-rich envelope. These stars blow strong H-poor winds. The inner part of the wind engulfing the star is dense and optically thick, and efficiently absorbs the ionizing continuum from the hot stellar surface. Farther from the star, the density drops and the wind becomes optically thin in the continuum, leading to a rich emission spectrum of recombination lines. Detailed models of such spectra can be calculated[1;7] and depend essentially on only three parameters: the effective temperature $T_{\rm eff}$ in the line-forming region, a normalized radius R_t (a combination of the stellar radius, luminosity, mass-loss rate, and wind terminal velocity[7]), and the chemical composition Z of the wind (assumed to be uniform, spherical, and of a constant mass-loss rate). The composition of the wind determines W-R spectral classes; stars with dominant He and N lines belong to the WN class (with those also showing traces of H usually denoted as WNh), stars with strong carbon lines belong to the WC class, and rare (and possibly hotter) stars with oxygen-rich spectra reside in the WO class[1].

Shortly after a W-R star explodes as a SN, the outer parts of the wind (extending in some cases[1] to $> 10^{13}$ cm) that have not yet been swept up by the expanding SN ejecta will emit strong recombination lines in response to ionizing flux released by the explosion shock breakout from the stellar surface. We estimate a factor of order 10^2–10^4 increase in ionizing luminosity, assuming an initial absolute magnitude range of $-2.5 < M < -10$ mag for the exploding W-R star[1] and a typical early-time luminosity of $M = -12.5$ mag for the resulting SN[3;5;8]. The effective temperature $T_{\rm eff}$ will also change, being very high ($> 10^5$ K) shortly after explosion[9] and decreasing with time as the shocked SN ejecta cool. The radiation illuminating the surviving W-R wind will thus effectively scan through the range of temperatures in W-R star line-forming regions. Since the wind parameters (composition, mass-loss rate, terminal velocity) do not change, the measured line spectrum observed shortly after explosion should be similar to that of a W-R star having the spectral class of the exploding progenitor (as the spectral classes reflect mainly the wind composition). The high wind densities around W-R stars (with electron densities $n_{\rm e} = 10^{11}$–$10^{12}\,{\rm cm}^{-3}$) imply short recombination times[10], $t_{\rm rec} \approx 3.9 \times 10^{12}\,(n_{\rm e}/{\rm cm}^{-3})^{-1}(T/10^4\,{\rm K})^{0.85}$ s, typically a few minutes for W-R densities and temperatures, so the emitted spectrum will promptly react to the rapidly evolving SN radiation field.

We obtained rapid spectroscopic observations of the recent Type IIb SN 2013cu (iPTF13ast) shortly after shock breakout (flash spectroscopy; see Methods). This event was first detected by the iPTF survey[11] on 2013 May 3.18 (UTC dates are used throughout this paper), photometrically confirmed 5.8 hr later, and promptly identified by an on-duty astronomer who triggered rapid follow-up observations[12], including an optical spectrum obtained just 4 hr later. Analysis of the early-time light curve of this SN (Extended Data Figure 1) suggests it exploded on May 2.93, implying that the first iPTF detection and the first spectrum correspond to only 5.7 hr and 15.5 hr after explosion, respectively. A full description of the SN and its evolution will be reported in a forthcoming publication[13]. We note that this event was independently discovered by the MASTER survey on May 5.3 (~ 2.3 days after explosion), and it was assigned the name SN 2013cu following spectroscopic confirmation[14].

Our first spectrum of SN 2013cu reveals a continuum and emission lines that bear a striking resemblance to spectra of W-R stars (Fig. 1a). According to accepted W-R terminology[1] the spectrum is classified as a WN6h (Fig. 1a, bottom); the relative strength of nitrogen to carbon lines precludes a WC classification, and the absence of any high-excitation oxygen lines is inconsistent with a WO star. The stronger lines (Hα, Hβ, N IV λ7115, and He II λ5411) exhibit a complex profile (Fig. 2) consisting of a relatively broad base ($\sim 2500\,\mathrm{km\,s^{-1}}$ full width at zero intensity; FWZI) on which prominent narrow, unresolved lines (FWZI $\approx$ 3Å; velocity dispersion $< 150\,\mathrm{km\,s^{-1}}$) are superimposed. This is consistent with predictions for W-R pre-SN wind velocities[15;16], though we cannot exclude the possibility that at least some of the observed line broadening is produced by electron scattering rather than genuine velocity dispersion. To the best of our knowledge, no similar spectra of a stripped (H-poor) SN have been acquired previously. W-R-like spectroscopic features have been observed in spectra of some H-rich (nonstripped) SNe obtained at substantially later epochs, and their typically much broader lines were interpreted as emerging from interaction with circumstellar material (CSM)[17]. We further discuss these previous observations in Extended Data Figure 3.

We analyze our very early spectrum using the PoWR grid of W-R spectral models[7] made available via a web interface at http://www.astro.physik.uni-potsdam.de/~wrh/PoWR/powrgrid1.html. We find an excellent fit with WN(h) models calculated assuming an H fraction of 20% (by mass) and temperature around 50,000 K. This temperature is consistent with the lower limit obtained from early *Swift* UV photometry (Extended Data Fig. 1). The essentially perfect match of the observed and modeled continuum shapes indicates that dust reddening must be negligible; any pre-existing dust must have been destroyed by the SN explosion flash (see Methods). We note that among the large catalog of Galactic WN stars specifically modeled in this manner[7], no stars drive winds which require more than 56% H by mass. Presumably, custom spectral fits[7] could be calculated and used to more accurately determine the physical parameters of the detected W-R wind. Assuming the spectrum was obtained 15.5 hr after explosion and a standard ejecta velocity of $10^4\,\mathrm{km\,s^{-1}}$, the narrow-line-emitting material must be located at radii above $\sim 5 \times 10^{13}$ cm in order not to have been swept up and accelerated by the expanding ejecta. This lower limit is consistent with the extent of some W-R winds, where the line-formation region extends out to several (5–10) times[18] the hydrostatic radius. Recent pre-SN W-R models[15] suggest hydrostatic radii of 10–20 solar radii for WN SN progenitors, consistent with line-formation regions extending to several hundred solar radii[1] or $> 10^{13}$ cm.

We further constrain the physical location of the wind using the following calculation. We measure the Hα line flux from our spectrum (calibrated to our host-subtracted photometry) and find $F_{\mathrm{H}\alpha} = 3.4 \times 10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. We translate this to line luminosity using a luminosity distance to the host galaxy UGC 9379 of $d = 108\,\mathrm{Mpc}$, calculated for a flat ΛCDM cosmology with $\mathrm{H_0} = 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.27$, and a redshift $z = 0.025734$, obtained from the NASA Extragalactic Database (NED), as well as negligible extinction, finding $L_{\mathrm{H}\alpha} = 4.8 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. We can then estimate[19] the pre-explosion H mass-loss rate $\dot{M} = 0.01 \times (L_{\mathrm{H}\alpha}/2 \times 10^{39}\,\mathrm{erg\,s^{-1}})^{1/2}\,(v_w/500\,\mathrm{km\,s^{-1}})\,(r/10^{15}\,\mathrm{cm})^{1/2}\,\mathrm{M_\odot\,yr^{-1}}$ assuming the lines are formed at a radius r via recombination, an emitting shell whose width is similar to its radius, spherical symmetry, and a wind profile with density falling as r^{-2}. We assume a wind velocity $v_w = 2500\,\mathrm{km\,s^{-1}}$, consistent with our spectra and as expected for W-R stars, but our results are not sensitive to this value and remain essentially unchanged for $100 < v_w < 2500\,\mathrm{km\,s^{-1}}$.

We check for self consistency by calculating the implied electron density, and hence the Thomson optical depth $\tau = 0.3\,(\dot{M}/0.01\,\mathrm{M_\odot\,yr^{-1}})\,(v_w/500\,\mathrm{km\,s^{-1}})^{-1}\,(r/10^{15}\,\mathrm{cm})^{-1}$ at this same radius, and require it to be lower than $\tau = 1$ for the lines to escape. We find that this self-consistency requirement places a lower limit on the line-formation region $r > 2 \times 10^{14}\,\mathrm{cm}$, with substantial mass-loss rates $\dot{M} > 0.03\,\mathrm{M_\odot\,yr^{-1}}$. Interpreting the disappearance of essentially all emission lines from our day 6 spectrum (Fig. 1b) as evidence that the wind was swept up by the expanding ejecta (moving at $10^4\,\mathrm{km\,s^{-1}}$), the radius of the line-emitting region must be $r < 5.2 \times 10^{14}\,\mathrm{cm}$, fully consistent with our estimates.

We can then calculate the total H mass by integrating over r: $M_\mathrm{tot} = 0.006\,(\dot{M}/0.01\,\mathrm{M_\odot\,yr^{-1}}) \times (v_w/500\,\mathrm{km\,s^{-1}})^{-1}\,(r/10^{15}\,\mathrm{cm})^{-1}\,\mathrm{M_\odot}$, indicating a range of $0.0008\,\mathrm{M_\odot} < M_\mathrm{tot} < 0.0035\,\mathrm{M_\odot}$ for the range of permitted H masses. Assuming the typical H abundances for WN(h) stars ($\sim 20\%$), the total wind mass (dominated by He) can be estimated to be several times larger than these numbers. Detailed simulations[20] show that as little as $0.1\,M_\odot$ of He-dominated CSM would result in strong spectroscopic interaction signatures (that we do not observe), consistent with our derived total masses.

We conclude that we have directly detected a W-R-like wind from the SN progenitor with a WN(h) spectral class, indicating a low H mass fraction. Assuming the wind composition we measure represents the surface composition of the progenitor star, our observations indicate that some members of the spectroscopic WNh W-R class explode after having lost most of the hydrogen envelope, exposing the CNO-processed, N-rich He layer below. Analysis of photometric and spectroscopic follow-up observations[13] confirms that the explosion was indeed a SN of Type IIb (Fig. 1c), as expected if the progenitor was a massive star that lost all but $\sim 0.1\,M_\odot$ of its H envelope[21].

Our observations have interesting implications. First, we note that the derived value of the mass-loss rate and emission-line-region size are quite extreme compared with known W-R observations and radiatively driven models[22], including models with clumpy, inflated atmospheres[23], suggesting that the mass-loss rate from the progenitor star may have increased shortly (of order one year for the assumed velocities) prior to its explosion. Interestingly, such pre-SN activity may be explained by recent wave-driven models[6], or perhaps more extreme envelope inflation[23] is indicated. These data can thus provide a key diagnostic of the final stages of nuclear core burning in massive stars, currently poorly understood, with potential deep implications into the explosion mechanism itself. In any case, the star probably exploded inside a thick wind, and the explosion shock may have broken out from the opaque inner wind rather than from the hydrostatic surface of the star[9].

Our finding is in general accord with some previous work on SN IIb progenitors. Direct imaging of the progenitor of SN 2008ax[24] is consistent with a WNh progenitor. Furthermore, increased mass loss during the final year prior to explosion may inflate the apparent photospheric radius of the pre-SN star, making stars with compact cores appear to have extended (low-mass) envelopes[23], possibly reconciling the conflicting findings about the progenitor of the Type IIb SN 2011dh[25–28]. Regardless of the exact mechanism, our observations suggest that substantial W-R-like winds predate at least some SNe IIb. A strong metallicity dependence of this process may explain the trend in the SN IIb/SN Ib ratios with host-galaxy metallicity[29]. Future studies of numerous additional supernova progenitors via their spectroscopic wind signatures (see Methods) would provide powerful constraints on the final stages of massive-star evolution.

Methods Summary Photometry: r-band observations were obtained by the iPTF survey telescope. Photometry is measured using our custom pipeline performing point-spread-function (PSF) photometry on iPTF images after removing a reference image constructed from pre-explosion data using image subtraction. *Swift* UV absolute AB magnitudes (Extended Data Fig. 1) are measured using standard pipeline reduction and are corrected for host-galaxy contamination using late-time *Swift* images. Spectroscopy: our earliest (15.5 hr) and latest (69 days) spectra were obtained using the DEIMOS spectrograph mounted on the Keck-II 10 m telescope using the 600 line mm^{-1} grating and an exposure time of 600 s. Additional spectra were obtained using ALFOSC mounted on the 2.56 m NOT telescope, LRS mounted on the 10.4 m HET telescope (day 3), and LRIS mounted on the Keck-I 10 m telescope (day 6). All spectra were reduced using standard pipelines and are digitally available on WISeREP. The method of flash spectroscopy is described in detail in the extended methods section.

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Author Contributions A.G. initiated the study, conducted analysis, and wrote the manuscript. I.A. found the SN, triggered rapid follow-up spectroscopy, and contributed to the light-curve analysis, observations, data reduction, and manuscript preparation. E.O.O. contributed to analysis of early-time data, mass-loss estimates, temperature evolution, and manuscript preparation. S.B. contributed to data reduction, and to early light-curve and spectroscopic analysis. S.B.C. reduced *Swift* and Palomar 60-inch data, and contributed to spectroscopic reduction and analysis. M.M.K. provided APO data and contributed to the manuscript preparation. Y.C. contributed to APO data reduction, early light-curve analysis, and manuscript preparation. O.Y. contributed to observations and manuscript preparation. D.T. provided unpublished SN light-curve templates and contributed to photometric analysis. J.M.S. provided spectroscopic reduction and advice, and contributed to HET spectroscopy. A.H. provided early Keck spectroscopy. A.D. contributed to observations and data reduction. F.T. reduced NOT data. J.S. provided NOT spectroscopy. D.P. provided Keck spectroscopy and analysis. P.V. assisted with observations, spectroscopic analysis, figure preparation, and manuscript writing. P.E.N. is a PTF builder and contributed to the manuscript. S.R.K. is a PTF builder. A.V.F.

provided Keck data and edited the manuscript. J.C.W. provided HET data.

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Methods

Photometry: r-band images were obtained by the iPTF survey camera mounted on the Palomar 48-inch Schmidt telescope[11,31]. Photometry is measured using our custom pipeline performing PSF photometry on iPTF images after removing a reference image constructed from pre-explosion data using image subtraction. *Swift* UV absolute AB magnitudes (Extended Data Fig. 1) are measured using standard pipeline reduction[32] and are corrected for host-galaxy contamination using late-time *Swift* images.

Spectroscopy: our earliest (15.5 hr) and latest (69 days) spectra were obtained using the DEep Imaging Multi-Object Spectrograph (DEIMOS[33]) spectrograph mounted on the Keck-II 10 m telescope using the 600 line mm^{-1} grating and an exposure time of 600 s. Additional spectra were obtained using ALFOSC mounted on the 2.56 m NOT telescope, LRS mounted on the 10.4 m HET telescope (day 3), and the Low Resolution Imaging Spectrometer (LRIS[34]) mounted on the Keck-I 10 m telescope (day 6). All spectra were reduced using standard pipelines and are digitally available on WISeREP[35].

Spectroscopic observations are presented in Fig. 1. **(a)** The early spectrum of SN 2013cu reveals W-R wind features. The spectrum (black) is compared with WNL models (red and gray curves, offset vertically for clarity)[7] showing remarkable similarity, both in line features (major species marked; strong He and N lines accompanied by Balmer lines indicate a WN6h classification) and in the continuum shape (demonstrated by overplotting the 56 kK model on the spectrum). The similarity in continuum shape to hot model spectra limits any dust reddening to be minimal, indicating that any pre-existing circumstellar dust must have been destroyed; compare with the observed spectrum of the WN6(h) star HD 192163 (blue). Consistent with this conclusion, we detect no trace of Na D absorption lines. **(b)** Emission-line evolution during the first week. We replot the first spectrum (red), compared with spectra obtained ~ 3 days after explosion (using ALFOSC, blue; and LRS, cyan) and ~ 6 days after explosion (magenta; see Ref.[13] for additional details). Spectra were scaled and offset for clarity with respect to the high-quality Keck/LRIS spectrum. Continuum shapes are identical (within calibration uncertainties) and consistent with the Rayleigh-Jeans tail of a hot

Planck curve, indicating that the blackbody peak remains in the UV at 6 days past explosion. By day 3 the initially strong W-R features disappear, with the exception of weaker He II lines and the C III/N III complex around 4640 Å (marked), while the Hα line remains constant at $3.4 \times 10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ (with decreased equivalent width due to higher continuum level). The high signal-to-noise ratio spectrum on day 6 is almost featureless, except for weak Hα emission (inset) with an intensity < 0.1 that of day 3, likely suggesting that the line-forming region has been cleared by the expanding ejecta. **(c)**: SN 2013cu is a SN IIb. A spectrum of SN 2013cu 69 days after explosion (black) is compared with the prototypical Type IIb SNe 1993J at age 60 days (red) and 2011dh at age 43 days (green), and with the typical nonstripped Type II-P SN 2004et at age 45 days (blue). To allow for slight age differences and expansion-velocity variations, we align all spectra in wavelength using the weak Fe II lines at 4924 Å, 5018 Å, and 5169 Å (marked with black vertical lines), as they are good tracers of the photosphere. SNe 2013cu, 2011dh, and 1993J exhibit strong He I absorption at 5876 Å, 7065 Å, and 7281 Å (marked with black vertical lines), while the weaker 6678 Å absorption is similar in SN 2013cu and SN 2011dh. These He I lines are not detected in the SN II-P spectrum at all. On the other hand, SN 2013cu shows weaker Balmer absorption (marked with magenta vertical lines), and the Hα absorption is not clearly defined. Both the spectral similarity to SNe 1993J and 2011dh and the strong He I lines compared to H indicate that SN 2013cu is spectroscopically a SN IIb.

Flash spectroscopy: we define as "flash spectroscopy" a set of spectroscopic data obtained shortly enough after a supernova explosion so that the observed spectrum is dominated by features related directly to the effects of the shock-breakout flash. In particular, flash-ionized CSM recombines and forms strong emission lines, revealing, for example, the elemental abundance and thus the W-R class of a SN progenitor. In addition, emission-line spectra provide a handle on the early temperature evolution, which is difficult to measure even using *Swift* UV photometry because the blackbody peak is initially too far into the UV. This study provides strong motivation for future investigations using dedicated rapid-response spectrographs such as FLOYDS[3,36] and SEDM[37] responding to real-time triggers from high-cadence wide-field surveys[12].

While W-R SN progenitor stars are difficult to study using pre-explosion imaging (owing to both intrinsic low luminosity in the optical/infrared bands[15;30] and the possible confusing effect of a bright O/B companion[3]), we demonstrate that they are amenable to study using the flash spectroscopy method. W-R stars belonging to the WNh class may have the most extensive winds[1;15]. Application of this method to WC/WO stars may require flash spectroscopy at even earlier epochs (~ 1 hr after explosion), before the SN ejecta sweep up the high-density wind. Reducing the latency between SN explosion and spectroscopy by an order of magnitude compared to our observations of SN 2013cu is possible using recently commissioned instrumentation (Extended Data Fig. 2).

Unlike studies of SN progenitors through pre-explosion imaging, the flash spectroscopy method can be applied to relatively distant objects (SN 2013cu is located 108 Mpc away, well beyond the 20 Mpc distance typical for pre-explosion studies), and to events in galaxies having no pre-explosion high-quality imaging, such as a large population of little-studied dwarf galaxies. Based on local SN rate measurements[38], ~ 300 events explode within 100 Mpc every year and can be potentially studied in this manner. The method thus allows routine spectroscopic studies of SN progenitors, previously only possible by extreme serendipity (e.g., for the progenitor of SN 1987A[39]). Within a few years, the flash spectroscopy method can be used to chart wind signatures from numerous SN progenitors, and in particular, the W-R progenitor population of stripped SNe may be studied systematically. We thus expect that this method will be broadly applied in the coming years.

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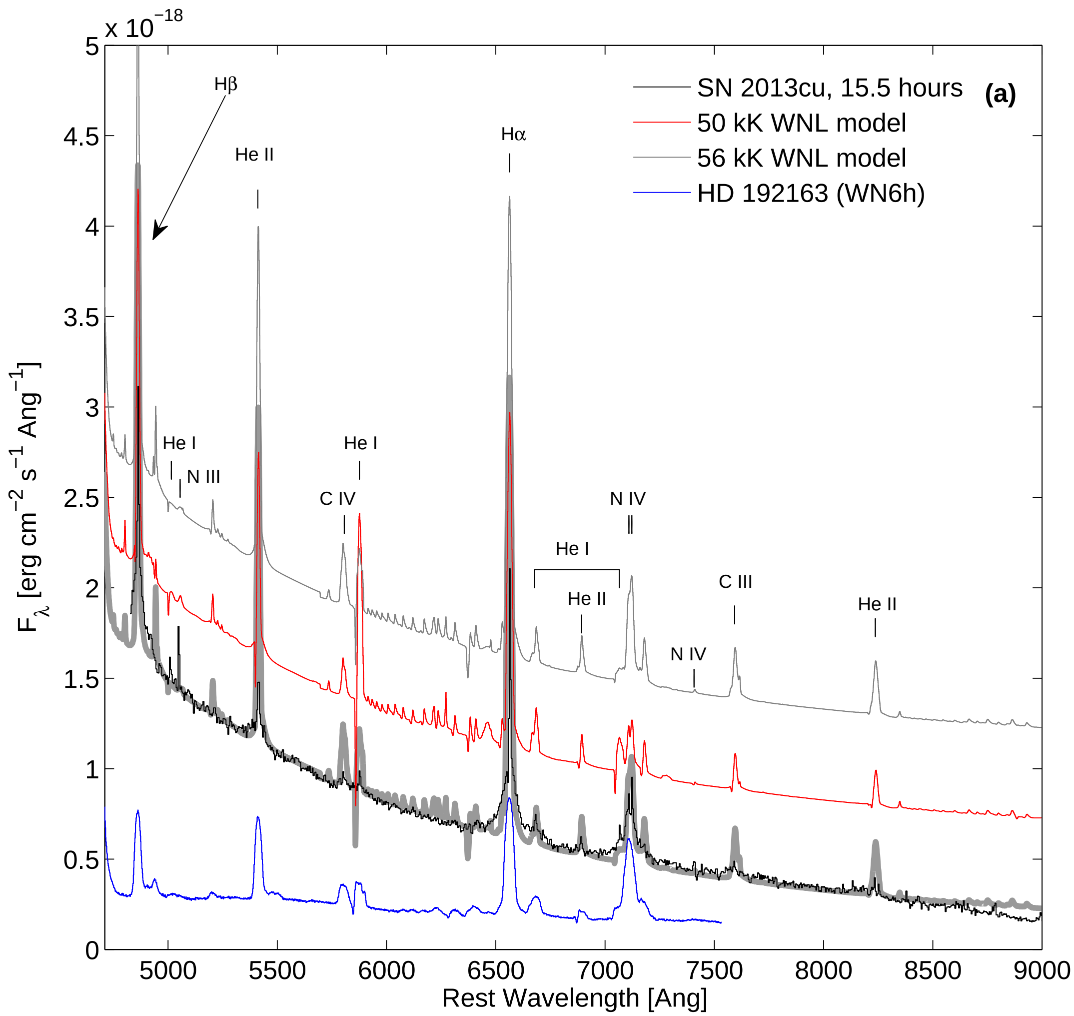
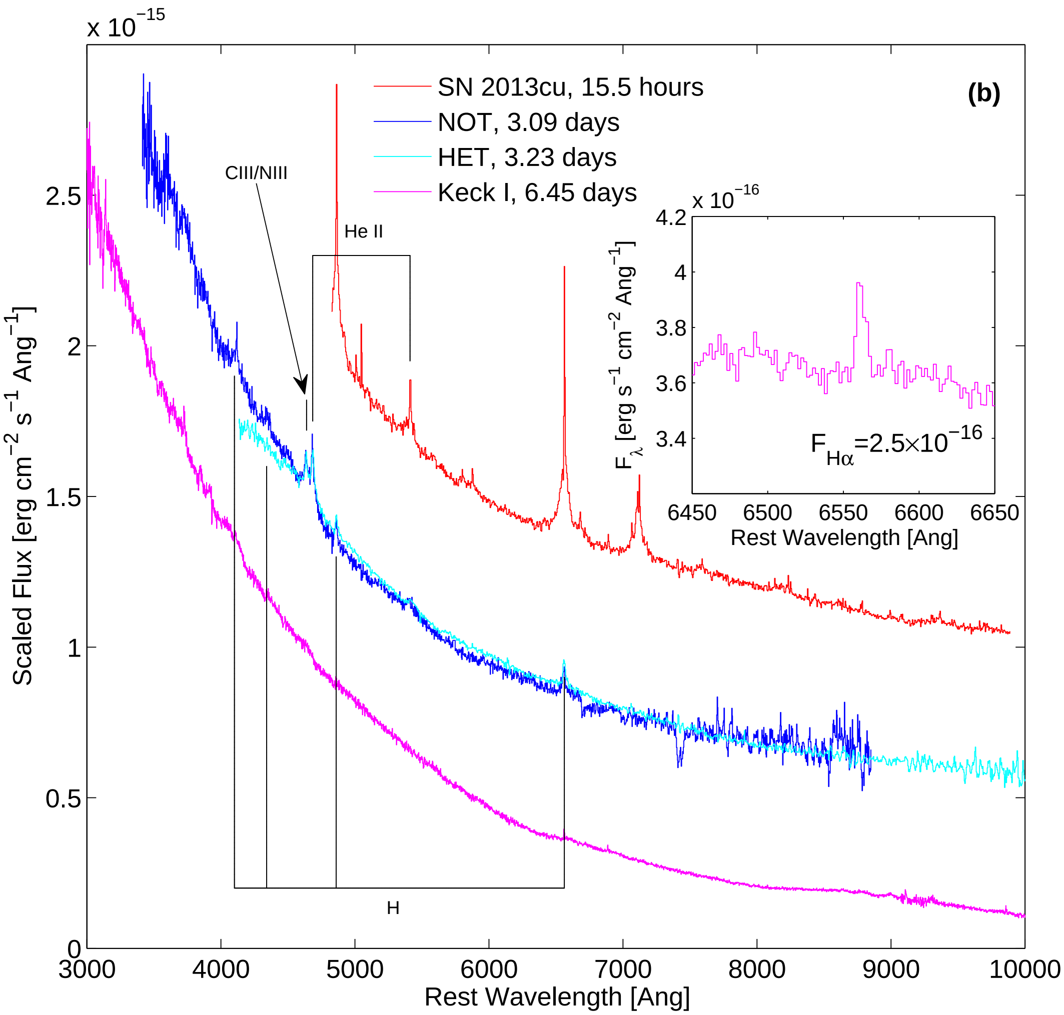
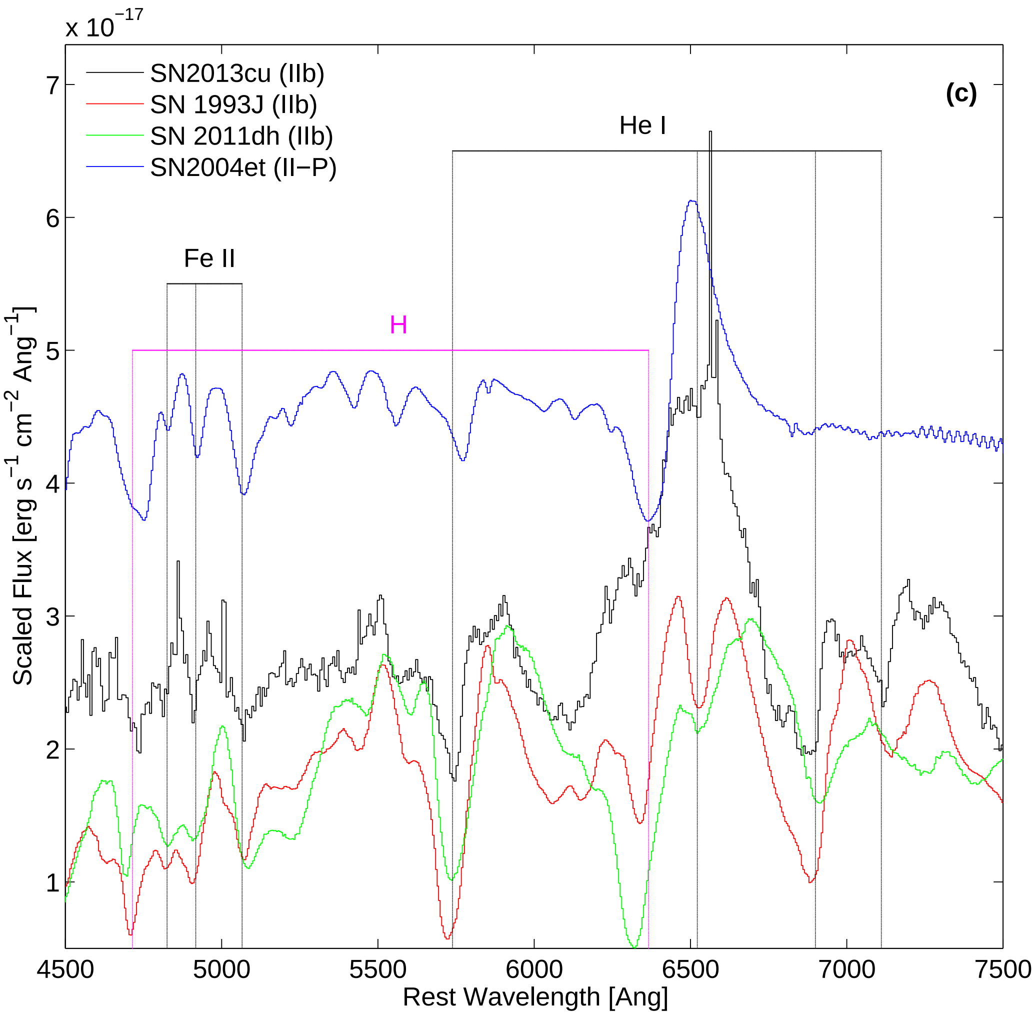


Figure 1: Spectroscopy of the Type IIb SN 2013cu reveals transient W-R-like features. **(a)** The early spectrum of SN 2013cu (black) is compared with WNL models (red and gray curves)[7] showing remarkable similarity in line features (strong He, N and Balmer lines indicate a WN6h classification) and in the continuum. **(b)** Emission-line evolution during the first week. The first spectrum (red) is compared with later spectra. By day 3 (blue+cyan) the initially strong W-R features disappear, while the Hα line remains constant at $3.4 \times 10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. The spectrum on day 6 (magenta) is almost featureless, except for weak Hα emission (inset) with an intensity < 0.1 that of day 3, likely suggesting that the line-forming region has been cleared by the expanding ejecta. **(c)**: SN 2013cu is a SN IIb. A spectrum of SN 2013cu 69 days after explosion (black) is compared with the prototypical Type IIb SNe 1993J (+60 days; red) and 2011dh (+43 days; green), and with the typical nonstripped Type II-P SN 2004et (45 days; blue). SNe 2013cu, 2011dh, and 1993J exhibit strong He I absorption at 5876 Å, 7065 Å, and 7281 Å (marked with black vertical lines), which are not detected in SNe II-P. See methods section for additional details.



x 10^−15
SN 2013cu, 15.5 hours
NOT, 3.09 days
HET, 3.23 days
Keck I, 6.45 days
(b)
CIII/NIII
He II
H
Scaled Flux [erg cm^−2 s^−1 Ang^−1]
Rest Wavelength [Ang]
x 10^−16
F_λ [erg s^−1 cm^−2 Ang^−1]
F_Hα=2.5×10^−16
Rest Wavelength [Ang]



x 10^-17
SN2013cu (IIb)
SN 1993J (IIb)
SN 2011dh (IIb)
SN2004et (II−P)
(c)
He I
Fe II
H
Scaled Flux [erg s^-1 cm^-2 Ang^-1]
Rest Wavelength [Ang]

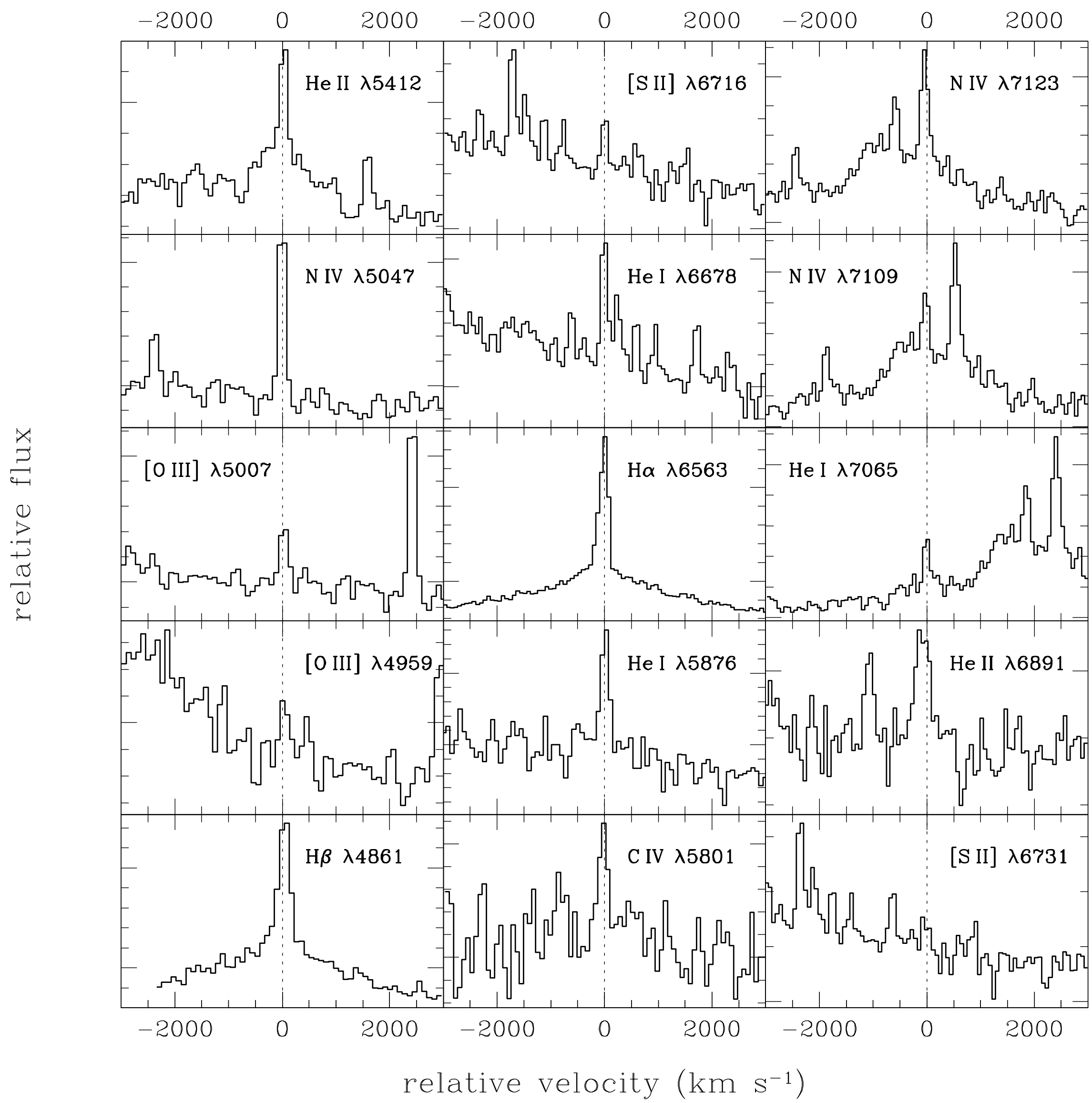
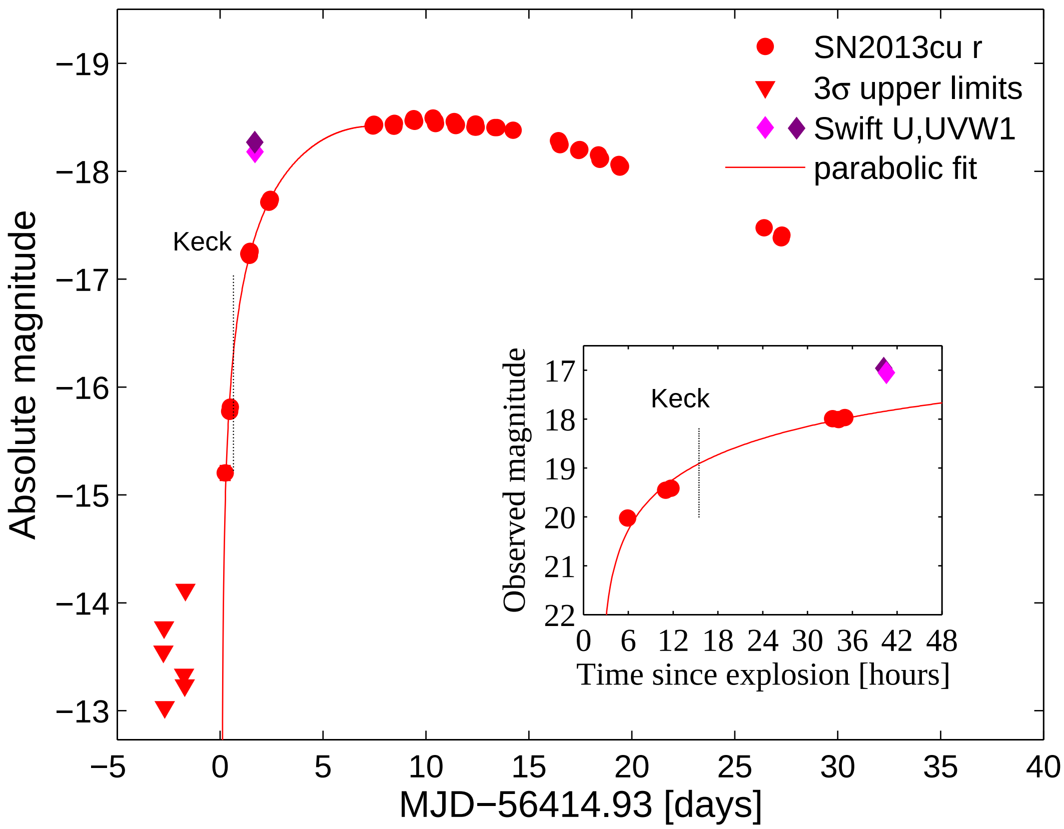
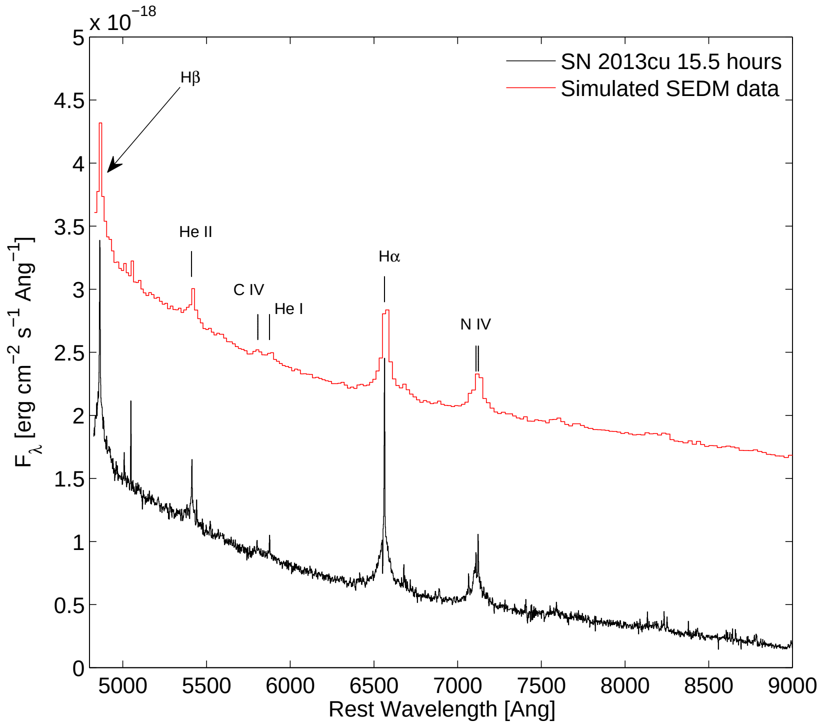


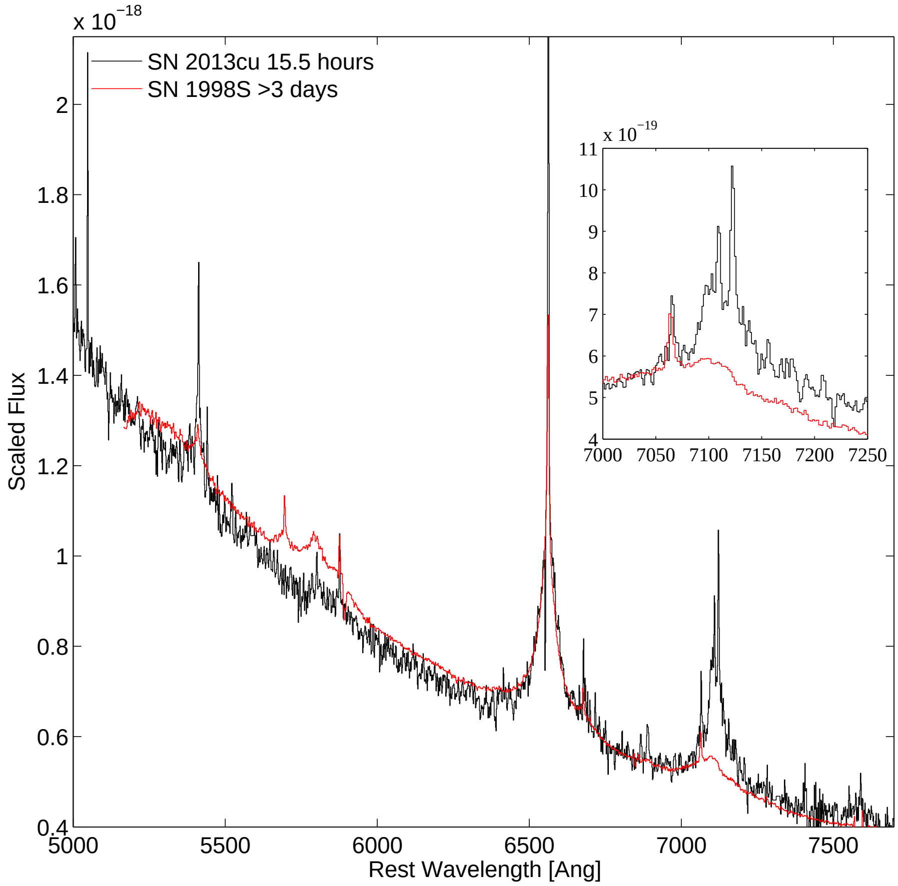
Figure 2: Emission-line velocity structure at 15.5 hr. The strongest lines (Hα and Hβ, He II λ5411, and the N IV λ7115 complex) show broad wings extending out to $\sim 2500\,\mathrm{km\,s^{-1}}$. Other weaker lines are narrow and unresolved.



Extended Data Figure 1: The r-band light curve of SN 2013cu. A parabolic model of the flux vs. time (red solid curve) describes the pre-peak data (1σ s.d. error bars) very well. Backward extrapolation indicates an explosion date of UTC 2013 May 2.93 ± 0.11 (MJD $= 56414.93$; 5.7 hr before the first iPTF detection; see inset); we estimate the uncertainty from the scatter generated by modifying the subset of points used in the fit. Our first Keck spectrum was obtained about 15.5 hr after explosion (vertical dotted line). Early *Swift* UV photometry (diamonds) places a lower limit of $T = 25{,}000\,\mathrm{K}$ on the blackbody temperature measured 40 hr after explosion.



Extended Data Figure 2: Flash spectroscopy — rapid spectroscopic observations of SNe during or shortly after shock breakout. This simulated SEDM spectrum (red) created by downgrading the observed Keck spectrum (black; resolution $R = 2000$) to the coarse SEDM resolution ($R = 100$) shows that the strong W-R lines (in this case the marked H, He, and N lines) are still easily detectable and allow us to determine the W-R spectroscopic class. The SEDM is an IFU low-resolution spectrograph designed for robotic response to transient events, to be mounted on the Palomar 60-inch telescope almost continuously. Responding to real-time triggers from the iPTF survey operating on the same mountain, this instrument should be able to obtain low-resolution spectra within $\sim 1\,\mathrm{hr}$ of object detection. Operating on a smaller telescope than Keck, SEDM data of similar quality to the simulated spectrum will require a relatively long integration. However, SEDM will be able to observe objects with much reduced latency, benefiting from stronger line intensities expected owing to stronger shock-breakout flash luminosity processed by a denser wind close to the progenitor star, potentially compensating for its reduced absolute sensitivity.



Extended Data Figure 3: Comparison with early "W-R" spectra of SN 1998S[17]. W-R-like features similar to those we observed were previously noted in two cases, SN 1983K[40,41] and SN 1998S, and persisted for many days after explosion. The spectra of SN 1983K, classified as a SN II-P, are unfortunately not available for comparison. Spectra of SN 1998S (Type IIn) are shown here. The spectra have a similar blue continuum slope and a similar Hα profile. The He II λ5411 and the N IV λ7115 complex are weaker in SN 1998S, and the strong lines of N and C (5806 Å) are broad, consistent with an origin in shocked CSM[17] rather than in an undisturbed W-R wind. The inset shows a close-up view of the strong N IV λ7115 complex. N emission from SN 1998S is weak compared with He I λ7065 and shows a smooth, broad profile, while SN 2013cu exhibits a broad base (2500 km s^{-1} FWHM) as well as strong and narrow (unresolved) N IV lines. These observations are consistent with an origin of the N emission of SN 1998S in shocked (and perhaps N-rich) CSM[17], while the narrow He I lines may come from a more distant, photoionized wind. In SN 2013cu even the narrow N lines are much stronger than He, indicating a wind with W-R-like composition at all radii.