LETTERS

Supernova 2007bi as a pair-instability explosion

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Stars with initial masses such that $10M_\odot \leq M_{\rm initial} \leq 100M_\odot$, where $M_\odot$ is the solar mass, fuse progressively heavier elements in their centres, until the core is inert iron. The core then gravitationally collapses to a neutron star or a black hole, leading to an explosion—an iron-core-collapse supernova[1,2]. By contrast, extremely massive stars with $M_{\rm initial} \geq 140M_\odot$ (if such exist) develop oxygen cores with masses, $M_{\rm core}$, that exceed $50M_\odot$, where high temperatures are reached at relatively low densities. Conversion of energetic, pressure-supporting photons into electron–positron pairs occurs before oxygen ignition and leads to a violent contraction which triggers a nuclear explosion[3–5] that unbinds the star in a pair-instability supernova. Transitional objects with $100M_\odot < M_{\rm initial} < 140M_\odot$ may end up as iron-core-collapse supernovae following violent mass ejections, perhaps as a result of brief episodes of pair instability, and may already have been identified[6–8]. Here we report observations of supernova SN 2007bi, a luminous, slowly evolving object located within a dwarf galaxy. We estimate the exploding core mass to be $M_{\rm core} \approx 100M_\odot$, in which case theory unambiguously predicts a pair-instability supernova. We show that $>3M_\odot$ of radioactive ^{56}Ni was synthesized during the explosion and that our observations are well fitted by models of pair-instability supernovae[9,10]. This indicates that nearby dwarf galaxies probably host extremely massive stars, above the apparent Galactic stellar mass limit[11], which perhaps result from processes similar to those that created the first stars in the Universe.

We identified a new optical transient (SNF20070406-008) on 2007 April 6.5 UT (universal time is used for all dates in this paper) at right ascension 13 h 19 min 20.2 s and declination 08° 55′ 44.0″ (J2000). Follow-up spectroscopic observations showed that this is a supernova (SN 2007bi), with no trace of either hydrogen or helium, leading to its classification as a type Ic supernova[12], albeit of a peculiar nature and with only one previously known counterpart (SN 1999as[13]; Fig. 1). No signs of interaction with circumstellar material (a major source of uncertainty in the analysis of previous luminous supernovae[7,14]) are observed throughout the evolution of this event (Fig. 1). A search for pre-discovery data recovered observations by the University of Arizona's Catalina Sky Survey[15] that allowed an accurate determination of the date and magnitude of the supernova brightness peak. Photometric observations continued for 555 days during our intensive follow-up campaign. A red (R-band) light curve is plotted in Fig. 2a.

The measured light curve is unique, showing a very long rise time to peak (~70 d; Fig. 2; Supplementary Information, section 2), an extreme luminosity reaching a peak R-band absolute magnitude of $M_{\rm R} = -21.3$ mag and a slow decline (0.01 mag d^{-1} over >500 d),

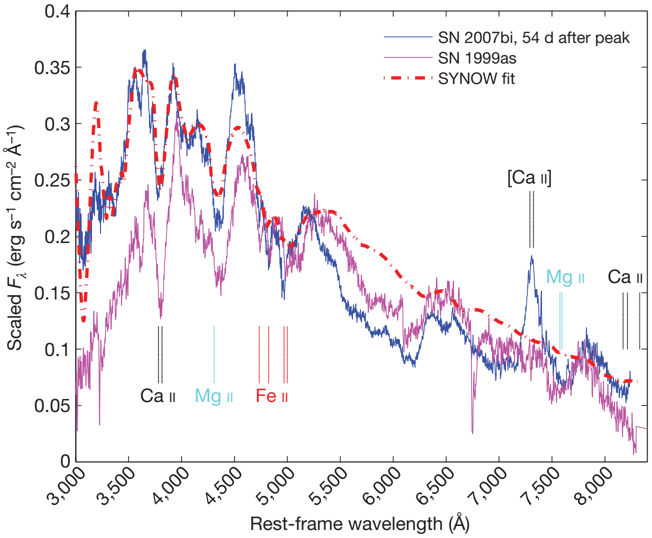

Figure 1 | Spectra of the unusual type Ic supernova SN 2007bi. We observed SN 2007bi on 2007 April 15.6 and 16.4, using the Low Resolution Imaging Spectrometer[26] (LRIS) mounted on the Keck I 10-m telescope (W. M. Keck Observatory, Hawaii). Here we plot the specific flux, F_λ, with arbitrary scaling. Narrow emission lines (see Fig. 3 for details) indicate a redshift of $z = 0.1279$. A survey of our databases of supernova spectra shows that this event is similar to only a single previous example, SN 1999as[13], which until now was the most luminous known type Ic supernova by a wide margin. SN 2007bi has a comparable luminosity (Fig. 2). We identify the most prominent features (marked) as arising from calcium, magnesium and iron, and derive a photospheric velocity of 12,000 km s^{-1}. A model fit (Supplementary Information, section 5) confirms these line identifications and shows that the absorption in the blue–ultraviolet part of the spectrum is dominated by blends of iron, cobalt and nickel lines. The shallow, poorly defined trough seen around 5,500–6,000 Å could arise from blends of silicon and sulphur lines, and the lines of neutral oxygen and sodium that are usually prominent in type Ic spectra are remarkably weak. No hydrogen or helium lines are seen, confirming the type Ic classification and strongly disfavouring the possibility that interaction with circumstellar material contributes significantly to the luminosity[7,14,27]. No narrow sodium absorption is seen, indicating little absorption by dust in the host galaxy[19]. The strong emission line around 7,300 Å seems to arise from [Ca II] emission at zero expansion velocity, and is usually observed in supernova only in late-time nebular spectra. A complete analysis of our full set of photospheric spectra will be presented in a forthcoming publication; see also additional details in ref. 19.

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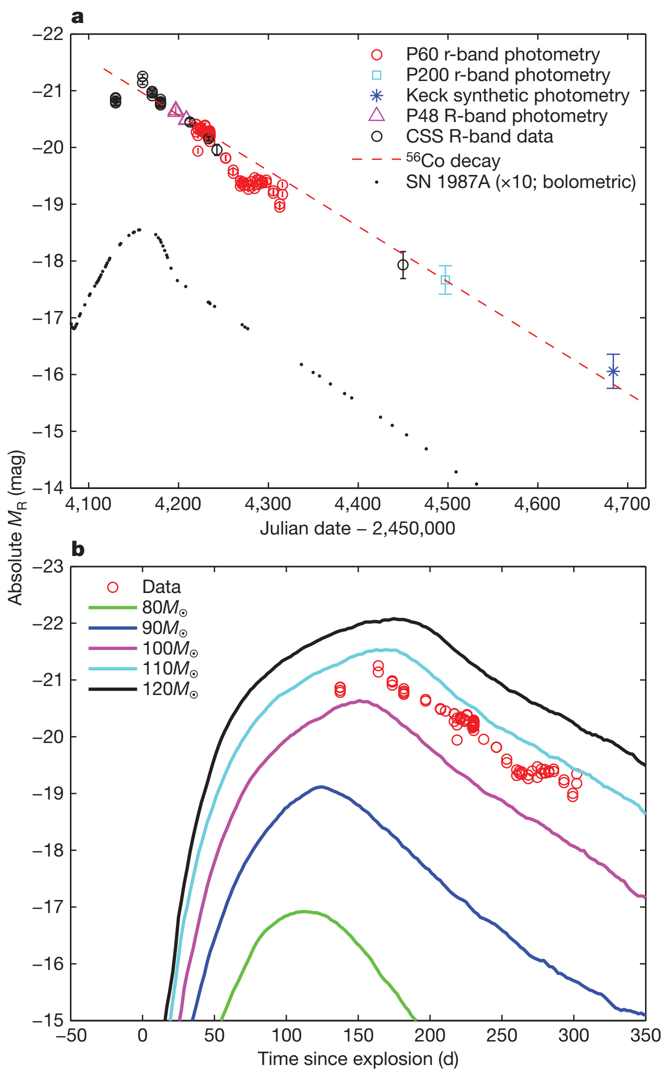

Figure 2 | Radioactive ^{56}Ni and total ejected mass from the light-curve evolution of SN 2007bi are well fitted using PISN models. **a**, The R-band light curve of SN 2007bi. We have compiled observations obtained using the 48-inch (1.2-m) Samuel Oschin Telescope (P48), the 60-inch (1.5-m) robotic telescope (P60) and the 200-inch (5-m) Hale Telescope (P200) at Palomar Observatory, California, as well as photometry from the Catalina Sky Survey[15] (CSS) and synthetic photometry integrated from our late-time Keck spectrum (Fig. 3; see Supplementary Information, sections 1 and 2, for additional details). We find a peak magnitude of $M_R = -21.3 \pm 0.1$ mag on 2007 February 21 (Supplementary Information, section 2). The error is dominated by the absolute zero-point calibration uncertainty. The outstanding peak luminosity of this event, if radioactively driven, suggests that a remarkable amount of ^{56}Ni was produced ($>3M_\odot$; ref. 28; Supplementary Information, section 3). The slow rise time derived from our fit (77 d; Supplementary Information, section 2), combined with the measured photospheric velocity (12,000 km s^{-1}; Fig. 1), requires very massive ejecta ($M_{ej} \approx 100M_\odot$) and a huge release of kinetic energy ($E_k \approx 10^{53}$ erg; Supplementary Information, section 3), where we apply the commonly used scaling relations[28,29]. An independent direct estimate for the ^{56}Ni yield is obtained from the luminosity during the late-time radioactive-decay phase, compared with the observed decay of SN 1987A[30] (Supplementary Information, section 3). Given the uncertainty in the explosion date of SN 2007bi and a range of bolometric correction values (Supplementary Information, section 2), the ^{56}Ni mass produced by SN 2007bi satisfied $4M_\odot < M_{^{56}Ni} < 7M_\odot$. The total radiated energy we measure by direct integration of the light curve is $E_{rad} \approx (1–2) \times 10^{51}$ erg (Supplementary Information, section 3), which is comparable to that of the most luminous supernovae known[7]. Errors, 1σ. **b**, Comparison of the observations of SN 2007bi with models calculated before the supernova's discovery[5,9]. The curves presented are for various helium cores (masses as indicated) exploding as PISNs, and cover the photospheric phase. The data are well fitted by $100M_\odot$–$110M_\odot$ models. At later times, the emission is nebular and bolometric corrections used to calculate the model R-band light curve cease to apply (Supplementary Information, section 4). In comparing with these rest-frame models, cosmological time dilation for $z = 0.1279$ has been taken into account.

consistent with the decay rate of radioactive ^{56}Co. These properties suggest that the very massive ejecta were energized by a large amount of radioactive nickel ($>3M_\odot$; Figs 2 and 3; Supplementary Information, section 3), as expected from models of pair-instability supernovae[4,5,10] (PISNs). Our spectra, lacking any signs of hydrogen or helium, indicate that this mass is dominated by carbon, oxygen and heavier elements. The large amount of kinetic energy released, $E_k \approx 10^{53}$ erg (Fig. 2; Supplementary Information, section 3), is comparable to those derived for the most energetic γ-ray bursts[16], placing this event among the most extreme explosions known. In Fig. 2b, we show theoretical light curves calculated from PISN models[5,9] before our discovery. The data fit the models very well, suggesting that we observed the explosion of a star with a helium core mass of around $100M_\odot$.

PISN models imply that such an explosion would synthesize $3M_\odot$–$10M_\odot$ of radioactive ^{56}Ni (Table 1). Such a large amount of newly synthesized radioactive material would energize the supernova debris for an extended period of time, ionizing the expanding gas cloud. Collisional excitation would lead to strong nebular emission lines, whose strength should be roughly proportional to the amount of radioactive source material, providing another testable prediction. Figure 3a shows a comparison of the nebular spectrum of SN 2007bi with that of the well-studied, ^{56}Ni-rich SN 1998bw, which produced $\sim 0.5M_\odot$ of radioactive nickel[17], suggesting that SN 2007bi produced $\gtrsim 7M_\odot$ of nickel (Supplementary Information, section 3), again supporting its interpretation as a PISN.

By modelling the nebular spectrum, we are able to resolve the elemental composition of the fraction of the ejected mass that is illuminated by radioactive nickel. We can directly measure the abundances of carbon, oxygen, sodium, magnesium, calcium and iron, and derive the mass of radioactive ^{56}Ni. Our elemental abundance ratios are in good agreement with model predictions[5] for heavier elements, but lighter elements (carbon, oxygen and magnesium) seem to be under-observed. By adopting the calculated model output[5] for elements that do not have strong nebular emission in the optical (mostly silicon and sulphur, and some neon and argon), we arrive at a total illuminated mass of $>50M_\odot$, with a composition as described in Table 1. We note that this falls well below the total mass derived from photometry, indicating that even the unprecedented amount of radioactive nickel produced by SN 2007bi was not sufficient to energize the entire mass ejected by this extreme explosion (Supplementary Information, section 6). The unilluminated mass probably contains more light elements that originated in the outer envelopes of the exploding star, and in which our nebular observations are deficient (see Supplementary Information, sections 3 and 6, for additional details).

Our data thus provide strong evidence that we have observed the explosion of a helium core with $M \approx 100M_\odot$, which, according to theory, can only result in a PISN[3–6,10,18]. The measured light curve, yield of radioactive nickel and elemental composition of the ejecta are consistent with models of PISNs that were calculated before our discovery. On the basis of fewer observations of SN 2007bi, combined with their analysis of the host-galaxy properties, the authors of ref. 19 consider both a PISN model and an interpretation in terms of a massive iron-core-collapse supernova[20], slightly favouring the latter. However, our quantitative estimate of the helium core mass from our peak light-curve shape and analysis of the nebular spectra is inconsistent with iron-core-collapse models[20] and theoretically requires a PISN[5,10]. We thus conclude that we have most likely discovered the first clear example of a PISN.

There are several implications of this discovery. Theory allows stars as massive as $1,000M_\odot$ to have formed in the very early Universe[21].

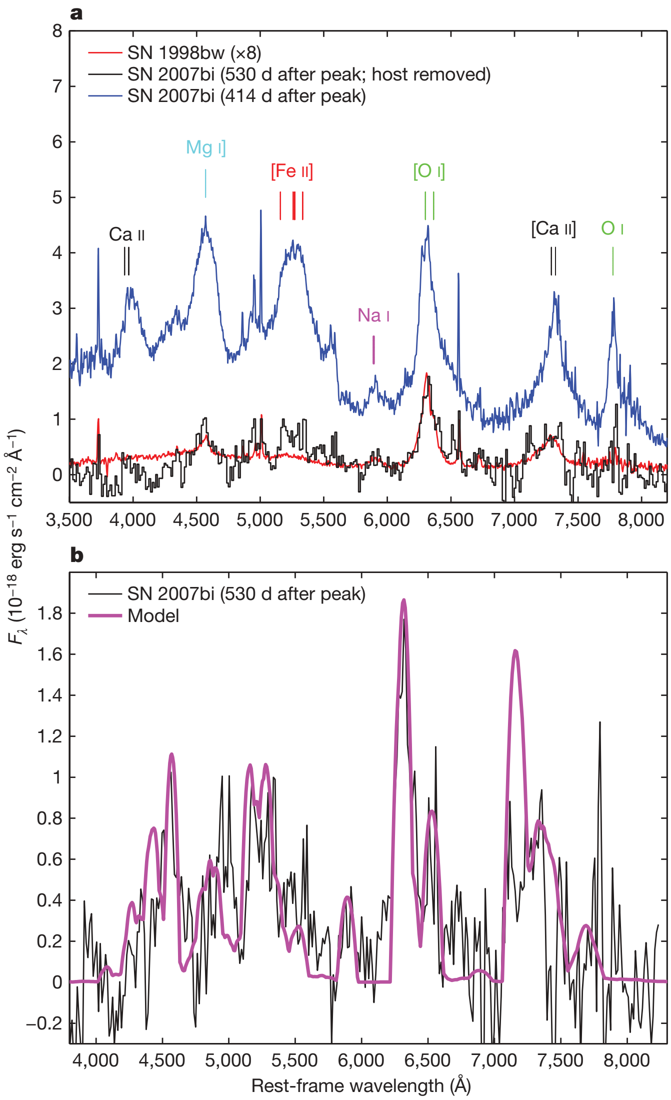

Figure 3 | Ejecta composition from nebular spectra of SN 2007bi. a, Two late-time spectra of SN 2007bi. A spectrum obtained with the FORS2 spectrograph mounted on the European Space Observatory's 8.1-m Very Large Telescope at the Paranal facilities of the La Silla Paranal Observatory, Chile, on 2008 April 10 (414 d after peak; 367 d rest frame) is not completely nebular yet. Prominent broad supernova emission peaks from neutral and singly ionized elements are marked. Multiple narrow host-galaxy emission lines ([O II], wavelength $\lambda = 3{,}727$ Å; Hβ; [O III], $\lambda = 4{,}959$ Å, 5,007 Å; Hα; [S II], $\lambda = 6{,}716$ Å, 6,731 Å) are seen at $z = 0.1279$. A later spectrum (530 d after peak; 470 d rest frame) was obtained using the LRIS mounted on the Keck I 10-m telescope on 2008 August 4. This spectrum is fully nebular, although of lower signal-to-noise ratio. Comparison with a late-time spectrum of the ^{56}Ni-rich SN 1998bw, which produced $0.5M_\odot$ of ^{56}Ni (ref. 17), adjusted for the larger distance and later rest-frame spectroscopic observations of SN 2007bi, and multiplied by eight, provides a good fit for intermediate-mass elements (oxygen, sodium, magnesium and calcium) but under-predicts the strength of the iron lines. Assuming that emission-line luminosity scales with the mass of energizing ^{56}Ni, we derive from the scaling factor a ^{56}Ni mass such that $7.7M_\odot < M_{^{56}\mathrm{Ni}} < 11.3M_\odot$ (Supplementary Information, section 3), in reasonable agreement with estimates from early (peak) and late-time (radioactive-tail) photometric estimates. We note that the lack of Hα emission at these late epochs is an especially strong argument against interaction with circumstellar material. A lower limit of $\sim 5 \times 10^{16}$ cm on the distance to any hydrogen-rich material (in particular recent mass loss) is derived from this non-detection assuming an expansion velocity of 12,000 km s^{-1} (Fig. 1). **b**, Modelling the nebular spectrum. By using our nebular spectroscopy code[17], we are able to constrain the composition of the ejecta. We find that the emission-line luminosity requires an initial ^{56}Ni mass of $3.7M_\odot$–$7.4M_\odot$ and the composition given in Table 1. As can be seen there, our measurements are well fitted by the theoretical predictions of PISN models[5] calculated before we discovered SN 2007bi.

However, the most massive stars known in the local Universe (for example luminous blue variables) have estimated masses of $\sim 150M_\odot$ (ref. 11). In the single example known so far, such a hypergiant star exploded in a normal core-collapse event (SN 2005gl)[2]. Our detection of a PISN forming from a $\sim 100M_\odot$ core suggests a progenitor with an estimated initial mass of $\sim 200M_\odot$ (ref. 5), assuming very low mass loss rates appropriate for zero-metallicity stars. We note that this estimate is highly sensitive to assumed mass-loss processes, which are poorly understood, and that high-metallicity mass-loss prescriptions would require an even higher initial mass. In a sense, our discovery of such a core is in conflict with commonly used mass-loss calculations, which do not allow such a high-mass core to form at the measured metallicities[19]. Our finding probably requires the modification of mass-loss models, perhaps through increased clumping in massive-star winds[7,14,18], at least during the hydrogen-rich mass-loss phase.

Regardless of the exact mass loss assumed, our data indicate that extremely massive stars above the Galactic limit ($M > 150M_\odot$) are formed in the local Universe. Perhaps the dwarf, metal-poor host galaxy of SN 2007bi ($M_B = -16.3$ mag at redshift $z = 0.1279$, indicating an approximate metallicity of $12 + \log[\mathrm{O/H}] = 8.25$ (ref. 22; see ref. 19 for additional details), where O and H respectively denote the number densities of atomic oxygen and hydrogen) retained conditions that were similar to those prevalent in the early Universe. Luminous events such as SN 2007bi can therefore serve as beacons, focusing our attention on otherwise unremarkable local dwarf galaxies that can be used as fossil laboratories to study the early Universe.

Our observational confirmation of PISN models supports their use in predicting the detectability and observed properties of PISNs formed from the first stars, by future missions such as NASA's James Webb Space Telescope; in estimating their contribution to

Table 1 | Predicted PISN ejecta elemental composition compared with our measurements

	C ($M_\odot$)	O ($M_\odot$)	Ne ($M_\odot$)	Na ($M_\odot$)	Mg ($M_\odot$)	Si ($M_\odot$)	S ($M_\odot$)	Ar ($M_\odot$)	Ca ($M_\odot$)	^{56}Ni ($M_\odot$)	Total ($M_\odot$)
Measured (1)	1.0*	10.1*	4.0	0.0012*	0.068*	22.0	10.0	1.3	0.75*	4.5*	53.8
Measured (2)	1.0*	12.0*	4.0	0.0013*	0.095*	22.0	10.0	1.3	0.90*	5.7*	57.1
Measured (3)	1.2*	14.6*	4.0	0.0018*	0.13*	22.0	10.0	1.3	1.00*	7.4*	61.7
Measured (4)	1.0*	7.5*	4.0	0.0015*	0.065*	22.0	10.0	1.3	0.95*	3.65*	50.6
Measured (5)	1.0*	9.1*	4.0	0.0018*	0.085*	22.0	10.0	1.3	1.10*	4.6*	53.3
Measured (6)	1.0*	11.3*	4.0	0.0023*	0.12*	22.0	10.0	1.3	1.00*	6.0*	56.8
$95M_\odot$ model[5]	4.1	45.2	4.0	0.0028	4.38	21.3	8.8	1.3	0.99	2.98	95
$100M_\odot$ model[5]	4.0	43.9	4.1	0.0028	4.41	23.1	10.0	1.5	1.22	5.82	100
$105M_\odot$ model[5]	3.9	42.7	3.9	0.0028	4.40	24.5	10.8	1.7	1.40	9.55	105
$95M_\odot$ model[10]	0.28	38.1	1.60	0.0011	2.35	20.9	13.5	2.32	1.98	5.18	95
$100M_\odot$ model[10]	0.25	36.4	1.51	0.0010	2.45	22.6	15.0	2.54	2.23	8.00	100
$105M_\odot$ model[10]	0.23	35.2	1.47	0.0009	2.47	23.9	15.9	2.73	2.46	11.89	105

We report six different estimates based on the two available late-time spectra (Fig. 3): Very Large Telescope day 414 (rows 1–3) and Keck day 530 (rows 4–6). Each spectrum is modelled assuming three different explosion dates: 45 d (rows 1, 4), 77 d (rows 2, 5) and 113 d (rows 3, 6) before peak (observed). The results are qualitatively similar, with ^{56}Ni masses of $3.7M_\odot$–$7.4M_\odot$ and total masses of $51M_\odot$–$62M_\odot$. Elements indicated with an asterisk are directly constrained from optical nebular emission lines. Abundances of other elements are probed through their cooling effects using lines outside the optical range (which are modelled), but we consider these constraints to be weaker.

the chemical evolution of the Universe[5]; and in calculating their effect on the reionization of the Universe. With the advent of new wide-field surveys, such as the Palomar Transient Factory[23,24] and the Catalina Real-Time Transient Survey[15], that monitor millions of nearby low-luminosity, anonymous galaxies[25], many additional such events should soon be discovered and will further illuminate these important questions.

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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 A.G.-Y. initiated, coordinated and managed the project, carried out photometric and spectroscopic analysis, and wrote the manuscript. P.M. was responsible for obtaining the Very Large Telescope late-time observations, carried out spectroscopic modelling and led the theoretical interpretation. E.O.O. led the Palomar photometry, obtained P200 and Keck observations, and performed the photometric calibration analysis. P.E.N. discovered SN 2007bi, identified its peculiarity and similarity to SN 1999as, initiated some of the early spectroscopic analysis and led the recovery of pre-discovery data from DeepSky and the Catalina Real-Time Transient Survey. S.R.K., M.M.K. and R.M.Q. obtained key late-time Keck spectra and helped with the P60 observations. A.V.F., S.B.C. and R.C. analysed early Keck data and contributed to manuscript preparation and editing, including final proofreading (A.V.F.). R.W. and D.K. carried out custom PISN modelling for comparison with the observations. M.S. undertook custom reduction of the key late-time Keck spectrum. E.C.B. is the principal investigator for the CSS, and his team acquired the CSS data and provided preliminary calibration of the results. A.J.D. helped recover CSS data and advised about their calibration. R.C.T. analysed early spectra using his automated SYNOW code. J.S.B., D.P. and A.A.M. obtained early spectroscopic observations of SN 2007bi as well as infrared observations using the Peters Automated Infrared Imaging Telescope, and contributed to analysis and manuscript editing. R.J.F. and J.M.S. contributed to spectral observations and reductions, and advised during manuscript preparation. I.A. helped with P60 photometry and calibration, and with manuscript editing. R.S.E. obtained Keck observations of SN 2007bi. J.D. contributed to the Very Large Telescope programme that resulted in the observations of SN 2007bi, and proofread the manuscript.

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