Rapid formation of large dust grains in the luminous supernova 2010jl

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The origin of dust in galaxies is still a mystery1–4. The majority of the refractory elements are produced in supernova explosions, but it is unclear how and where dust grains condense and grow, and how they avoid destruction in the harsh environments of star-forming galaxies. The recent detection of 0.1 to 0.5 solar masses of dust in nearby supernova remnants5–7 suggests in situ dust formation, while other observations reveal very little dust in supernovae in the first few years after explosion8–10. Observations of the spectral evolution of the bright SN 2010jl have been interpreted as pre-existing dust11, dust formation12,13 or no dust at all14. Here we report the rapid (40 to 240 days) formation of dust in its dense circumstellar medium. The wavelength-dependent extinction of this dust reveals the presence of very large (exceeding one micrometre) grains, which resist destruction15. At later times (500 to 900 days), the near-infrared thermal emission shows an accelerated growth in dust mass, marking the transition of the dust source from the circumstellar medium to the ejecta. This provides the link between the early and late dust mass evolution in supernovae with dense circumstellar media.

We observed the bright (V ≈ 14) and luminous (M_V ≈ −20) type IIn supernova 2010jl (ref. 16) with the VLT/X-shooter spectrograph covering the wide wavelength range 0.3–2.5 μm. Peak brightness occurred on 2010 October 18.6 UT, and observations were made at nine early epochs and at one late epoch, 26–239 days and 868 days past peak, respectively (Methods, Extended Data Table 1, Extended Data Figs 1–5). Figure 1 shows the intermediate-width components of the hydrogen emission lines of H\(_\gamma\) at a wavelength of 1.28 μm (b) and P\(_\beta\) at 868 days (d). The [O I] 6,300.304, 6,363.776 doublet (zero velocity set at λ6,300.304). The dashed-dotted lines in all panels denote zero velocity, at redshift z = 0.01058, as determined from narrow emission lines in the spectrum.

Figure 1 | Evolution of the hydrogen and oxygen line profiles in the spectrum of SN 2010jl. Line profiles for H\(_\gamma\)4,340.472 (a) and P\(_\beta\)λ12,818.072 (b) for epochs from 26 days to 239 days and H\(_\gamma\) and P\(_\beta\) at 868 days (c). The [O I] 6,300.304, 6,363.776 doublet (zero velocity set at λ6,300.304). The [O I] λ112.297.68 line. The dashed-dotted lines in all panels denote zero velocity, at redshift z = 0.01058, as determined from narrow emission lines in the spectrum.

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longer wavelengths, as expected if the attenuation of the lines is due to dust extinction, and rules out that the blueshifts are due to electron scattering\textsuperscript{14} (Supplementary Information). The early epoch hydrogen lines have a Lorentzian half-width at half-maximum (HWHM) in the range 1,000–2,000 km s\textsuperscript{-1}. The middle and right panels of Fig. 1 show that the line profiles at the late epoch are narrower (HWHM \approx 800 \pm 100 \text{ km s}^{-1}) and also exhibit blueshifts of the oxygen lines, which indicates that ejecta material is involved in the dust formation at this stage.

Figure 2 shows the temporal evolution of the inferred extinction $A_\lambda$, as derived from the attenuation of emission lines in the early spectra. We calculated the extinction from the ratios of the integrated line profiles at each epoch. We assume that the first epoch at 26 days past peak is nearly unextinguished and use it as a reference. The monotonic profiles at each epoch. We assume that the first epoch at 26 days past peak is nearly unextinguished and use it as a reference. The extinction at 239 days is $A_\lambda \approx 0.6$ mag. Interestingly, the shape of the normalized extinction curve shows no substantial variation with time. Scaling and combining the data from the eight individual early epochs allowed us to produce the first directly measured, robust extinction curve for a supernova. The extinction curve is shallow, with $R_V = A_V/(E(B-V)) \approx 6.4$, and can be represented by a mix of grey extinction dust grains ($A_\lambda$ is a constant) and either standard Small Magellanic Cloud or Milky Way extinction\textsuperscript{19}. The extinction contribution of the grey dust is 40% in the V band. We fitted several dust models to the extinction curve using amorphous carbon dust characterized by a power-law grain size distribution\textsuperscript{20} with slope $\alpha$, and minimum and maximum grain radii ($a_{\text{min}} < a_{\text{max}}$) in the interval [0.001, 5.0] \mu m.

Figure 3 shows the resulting confidence interval for the two parameters $a_{\text{max}}$ and $\alpha$ around the best-fit values of $a_{\text{min}} = 0.001 \mu m$, $a_{\text{max}} = 4.2 \mu m$ and $\alpha = 3.6$. It is evident that only size distributions extending to grain radii that are significantly larger than that of Milky Way interstellar-medium\textsuperscript{21,22} dust (\approx 0.25 \mu m) can reproduce the supernova extinction curve (Fig. 2). The 2\sigma lower limit on the maximum grain size is $a_{\text{max}} > 0.7 \mu m$. We cannot perform a similar analysis of the late epoch because the intrinsic line profile at this epoch is unknown and is likely to be strongly affected by extinction\textsuperscript{13}. However, we note that the blueshift velocities change little with wavelength (Extended Data Fig. 6), suggestive of large grains also at this epoch.

Figure 4 illustrates the continuous build-up of dust as a function of time. The increasing attenuation of the lines is accompanied by increasing emission in the near-infrared (NIR) spectra, from a slight excess over a supernova blackbody fit at early times to total dominance at the late epoch. We fitted the spectra with black bodies, which for the NIR excess yield a constant blackbody radius of $(1.0 \pm 0.2) \times 10^{16} \text{ cm}$ at the early epochs, and a temperature that declines from \approx 2,300 K to \approx 1,600 K from day 26 onwards. At the late epoch, we obtain a blackbody radius of $(5.7 \pm 0.2) \times 10^{16} \text{ cm}$ and a temperature of \approx 1,100 K. The high temperatures detected at the early epochs suggest that the NIR excess is due to thermal emission from carbonaceous dust, rather than silicate dust, which has a lower condensation temperature of about 1,500 K (ref. 1). The high temperatures rule out suggestions that the NIR emission is due to pre-existing dust or a dust echo\textsuperscript{11} (Extended Data Figs 7 and 8, and Supplementary Information). Fitting the NIR excess with a modified black body, assuming the grain composition found in our analysis of the extinction curve (Fig. 3), gives a dust temperature similar to the black-body temperature, which is at all epochs (and at all dust compositions considered) larger than 1,000 K. The dust masses inferred from the extinction and NIR emission agree very well. The inferred amount of dust at the late epoch (868 days) is \approx 2.5 \times 10^{-3} M_\odot (where $M_\odot$ is the mass of the Sun) if composed of carbon, but could be up to an order of magnitude larger for silicates (Methods). Our results indicate accelerated dust formation after several hundred days. SN 2010jl will

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**Figure 2** | Supernova dust extinction curves. a, The evolution of the extinction $A_\lambda$ of the hydrogen lines (open circles with standard deviations; see Methods). The solid lines represent the (linearly interpolated) extinction curves. b, The grey-shaded area represents the range of extinction curves relative to $A_\lambda$ (filled triangles with error bars). Grey curves are the Small Magellanic Cloud and Milky Way extinction curves, while the red curves include a grey component (Methods). c, Fits to the optical depth within the 1σ, 2σ and 3σ (68.3%, 95.4% and 99.7%) confidence intervals (Methods). Dashed and solid curves are models with ‘best fitting’ and Milky Way parameters, respectively.

**Figure 3** | Maximum grain size and slope of the grain size distribution. Confidence contours, as constrained by the normalized optical depth $\tau(\lambda)$ (see Fig. 2). The most favourable power-law models lie within a parameter range for $\alpha$ (the power-law slope of the grain size distribution) between about 3.4 and 3.7 and require large grains of $a_{\text{max}} \geq 1.3 \mu m$ (1σ). The confidence limits are as in Fig. 2. Even at the 3σ confidence limit the maximum grain size is larger ($a_{\text{max}} \approx 0.5 \mu m$) than Milky Way maximum grain sizes for a power-law model ($a_{\text{max}} = 0.25 \mu m$) (ref. 20), or more sophisticated models\textsuperscript{21,22}.

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METHODS SUMMARY

We obtained optical and near-infrared medium-resolution spectroscopy with the European Southern Observatory’s Very Large Telescope (VLT)/X-shooter instrument of the bright type IIn supernova 2010jl at ten epochs between 2010 November 13.4 to 2013 March 4.0 UT. The continuum emission of the spectra was fitted with a combination of black-body, modified black-body and host galaxy models, allowing us to quantify the temporal progression of the temperature and radius of the photosphere as well as the temperature and characteristics of the dust forming, which causes conspicuous excess near-infrared emission. We analysed the profiles of the most prominent hydrogen, helium and oxygen emission lines. From Lorentzian profile fits, which are good representations of the emission lines, we measured the blueshifts of the peaks and the HWHM of the lines, and derived the wavelength-dependent attenuation properties of the dust forming at each epoch. The uncertainties were obtained using Monte Carlo calculations by varying the Lorentzian profile parameters. We generated synthetic UVBRJKH light curves and calculated the energy output of the supernova. This, together with calculated dust vaporization radii, temperatures of the dust grains at different distances from the supernova, and the radius evolution of the forward shock, were used to constrain the location of the dust as it formed. Different dust models, characterized by either single grain sizes or a power-law grain-size distribution function and either amorphous carbon or silicate, were fitted to the extinction and the near-infrared excess emission. From these fits, we derived the temporal progression of the dust mass of the dust as it formed at each observed epoch.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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**Supplementary Information** is available in the online version of the paper.

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**Author Contributions** C.G. and J.H. conducted the observational campaign, reduced and analysed the data and wrote the manuscript. D.W. was the Principal Investigator of the observing programmes and assisted in writing the manuscript. E.D. performed calculations of vaporization radii and assisted in writing the manuscript. O.F. and G.L. assisted in data analysis. J.R.M. helped with the interpretation of the spectra and line profiles. D.M. and D.W. assisted with observations. A.C.D.-J. conducted the observation of the epoch 2 spectrum. All authors were engaged in discussions and provided comments on the manuscript.

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METHODS
We observed the type Ib SN 2010jl in UGC 5891A at ten epochs between 2010 November 13.4 UT and 2013 March 4.0 UT, following its discovery on 2010 November 3.5 UT (ref. 31). The supernova was first detected from the All Sky Automated Survey North on 2010 October 9.61 UT and peaked on 2010 October 18.6 UT (ref. 32). The time of explosion is unknown, but we assume a time of rise to peak of about 40 days. We adopt a luminosity distance of D = 45.7 Mpc to the supernova, based on our measured redshift of z = 0.01058.

The observations were obtained with the X-shooter echelle spectrograph33,34 mounted at the Cassegrain focus of the Kueyen unit of the Very Large Telescope (VLT) at the European Southern Observatory (ESO) on Cerro Paranal, Chile. The X-shooter instrument allows for simultaneous spectroscopic observations in three different arms, the ultraviolet and blue (UVB), visible (VIS) and near-infrared (NIR) wavebands, covering the continuous wavelength range of 0.3–2.5 μm. The observations were performed at the parallactic angle, with nodding between exposures along the 11° slit (see Extended Data Table 1 for details). The spectra were obtained under the following conditions: clear sky and in some cases thin cirrus, average seeing of ~1.2–2.0. For the majority of the observations we used slit widths of 1.0” (UVB), and 0.9” (VIS and NIR) giving resolving powers of 5,100 (UVB), 8,800 (VIS) and 5,300 (NIR), except for the second epoch on 2010 December 1.4 UT where, owing to mediocre seeing conditions of around 1.7”, we used wider slit widths of 1.6” (UVB), and 1.5” (VIS and NIR), leading to reduced resolving powers of 3,300 (UVB), 5,400 (VIS) and 3,500 (NIR). For all epochs, observations of spectrophotometric standards were performed using a slit width of 5.0”.

We used versions 1.5.0 and 2.2.0 of the X-shooter pipeline35 in physical mode to reduce the supernova and the standard star spectra to two-dimensional bias-subtracted, flat-field corrected, order-rectified and wavelength-calibrated spectra in counts. To obtain one-dimensional spectra the two-dimensional spectra from the pipeline were optimally extracted36. Furthermore, the spectra were slit-loss corrected, flux calibrated and corrected for heliocentric velocities. Additionally, telluric corrections were applied. All calibration and correction procedures after the basic pipeline reduction were performed using custom IDL programs. The spectra were corrected for a Galactic extinction along the line of sight to the supernova of E(B-V) = 0.027 mag (ref. 37).

We measured the blueshifts of the peaks (Extended Data Fig. 6). To properly fit the hot dust emission we therefore used a modified black-body function. The fit to the spectra is computed as

\[ F(l) = B(l, T_{SN}) R^2_{SN} \int ln^2 N_a \int d(\lambda) f(\lambda) n(\lambda) d\lambda \]

where B(l, T) is the Planck function at temperature T = T_{SN} for the supernova and T = T_{host} for the dust, R_{SN} is the radius of the supernova photosphere, D is the luminosity distance to the supernova, N_d is the total number of dust particles, m_d(\lambda) = (4\pi/3)\rho a^3 is the mass of a single dust grain of radius a and \kappa_d(\lambda) is the dust mass absorption coefficient for an assumed dust composition, that is, amorphous carbon and silicates. All the mass density \rho = 1.8 g cm^{-3} for amorphous carbon and \rho = 3.3 g cm^{-3} for silicates. We used a power-law grain size distribution function \phi(a) \propto a^{-\alpha}, which is normalized to unity in the interval [a_{min}, a_{max}) as

\[ \int f(a) da = 1. \]

Extended Data Fig. 2 depicts supernova spectra obtained at 44 days, 196 days and at a late epoch of 868 days. The adopted grain size distribution assumes the parameters \alpha, a_{min} and a_{max} from the best-fitting amorphous carbon model obtained from the extinction curves (Figs 2 and 3). To fit the spectrum at 868 days we exchanged the supernova black-body with a power law for the host galaxy continuum emission, expressed as C_{norm} \times \lambda^{-1.5}, where C_{norm} is a normalization constant and the power law exponent resulted from the fit. Additionally, for this epoch we explored two dust compositions, that is, amorphous carbon and silicates, and models with single grain sizes a between 0.001 μm and 10.0 μm, as well as grain-size distribution models varying \alpha between 2.0 and 4.5. We found (1) that amorphous carbon single-grain-size models as well as grain-size distribution models prefer large grains (1–5 μm), (2) that the quality of the fits of silicate models is fairly insensitive to the size of the grains and can accommodate small grains, (3) that we are unable to produce models with temperatures less than ~1,000 K, and (4) that the inferred dust masses for silicate grains are typically up to an order of magnitude higher than for amorphous carbon. All spectra are well fitted by a supernova temperature T_{SN} = 7,300 K and a dust temperature T_{dust}, which decreases from approximately 2,300 K to 1,600 K during the first 239 days, down to approximately 1,100 K at 868 days.

Analysis of line profiles. The spectra exhibit a richness of emission lines on top of the continuum, featuring in particular hydrogen and helium lines, which are: H\alpha λ=101.734, H\beta λ=496.52, H\gamma λ=468.615, He\i λ=587.621, H\delta λ=562.79, He\i λ=550.3, H\gamma λ=540.278, P\i λ=100.498, H\i λ=1035.199, P\ii λ=10192.1, Pf λ=21281.072 and Br\gamma λ=24765.268. The lines have a narrow (~100 km s^{-1}) velocity component on top of an intermediate-width velocity component. For H\beta, H\delta, H\gamma, He\i λ=587.621 and He\i λ=10380.199, the narrow lines exhibit a characteristic P Cygni profile (that is, a blue-shifted absorption and redshifted emission component). Only a subset of the hydrogen lines is suitable for quantitative extinction studies. We required that the lines exhibit a clear single-peaked intermediate-velocity component across all epochs, which can be well represented by a Lorentzian profile, not necessarily centred at the zero velocity (Extended Data Fig. 3a). None of the H\i lines are suitable for extinction studies because they show conspicuous bumps in the wings. Moreover, the wings significantly broaden with time (Extended Data Fig. 3b). The He\i λ=10380.199 line is blended with the Pf λ=10192.17 line, ruling out both lines for our study. The Pf λ=10192.17 line is located at the crossover between the X-shooter VIS and NIR arms, giving rise to unreliable flux calibration and background subtraction.

Some lines show the presence of large velocities. Extended Data Fig. 4 shows H\beta P Cygni profiles featuring velocities up to ~20,000 km s^{-1} which arise from the fast expanding thin outer layers of the supernova ejecta. The bulk expansion velocity of the supernova ejecta (corresponding to the minimum of the P Cygni profile) is around 7,300 km s^{-1}. Other lines, for example, H\gamma, are characterized by an underlying broad velocity component. As shown in Extended Data Fig. 5a, we can fit the 26-day H\gamma line with a combination of a broad Gaussian with a full-width at half-maximum of ~5,000 km s^{-1} and an intermediate Lorentzian with HWHM = 800 km s^{-1} centred at zero velocity. Although the H\gamma line is often used to demonstrate the effect of dust attenuation of the red wing, it is discarded for our study because of the progressive broadening of the wings (Extended Data Fig. 3b), which prevents a straightforward quantitative analysis.

At 868 days the emission lines no longer exhibit a broad velocity component. The intermediate velocity components of the hydrogen emission lines feature velocities up to ~2,000–3,000 km s^{-1} similar to the oxygen [O\i] λ6300.304 and [O\i] λ11297.68 Fl (Fig. 1). The lines are not well represented by Lorentzian profiles (Fig. 1, middle panel). Consequently, the late epoch is not considered for our quantitative extinction studies.

From single Lorentzians fits to H\alpha, H\beta, H\gamma, P\ii and Br\gamma, we estimated the Lorentzian HWHM of the intermediate-velocity components of these lines (about 1,500 km s^{-1}) (Extended Data Fig. 5b). Extended Data Fig. 5b shows that the hydrogen lines (for example, H\beta) exhibit deviations from symmetry, despite being adequately represented by Lorentzian profiles for our purposes (Extended Data Fig. 3a). We also measured the blueshifts of the peaks (Extended Data Fig. 6).

To obtain the hydrogen line profiles (Fig. 1), the spectrum from each epoch was continuum-subtracted and scaled to the first epoch. The scaling was set by the velocity at which the blue side of the line changed from being extinguished to being unextinguished (between ~1,200 km s^{-1} and ~1,000 km s^{-1}). This ensures that we measure only the extinguished parts of the lines. The blue unextinguished wings from all epochs coincide. At the late epoch (868 days), H\gamma was scaled to P\ii at a velocity of ~800 km s^{-1}. Extinction measurements. Attributing the red depressions to dust, we calculated the extinction (Fig. 2a) from the fitted Lorentzian profiles as \tau = -2.5log(h(\lambda)/I_\lambda(\lambda)), where I_\lambda(\lambda) is the line profile integrated over a velocity range extending from the scaling velocity up to 4,000 km s^{-1} and \lambda is the integrated line profile from the first epoch which was taken as a reference. We obtained the error bars of \tau (standard deviations) using Monte Carlo calculations by varying the fit parameters of the Lorentzian line profiles within their uncertainties. The error bars reflect the signal-to-noise ratio of the lines and the extent to which they are well represented by Lorentzians. From measurements of A(V) \lambda = 5.05 Å and E(B-V) in Fig. 2, we directly infer \tau = A(V)/E(B-V) = 6.4. The wavelength-dependent optical depth is fitted with (1) a phenomenological model based on grey dust plus either Small Magellanic Cloud or Milky Way dust, \tau_{SMC,MW}(\lambda), as \tau = \tau_{SMC,MW}(\lambda) + A_{opt} + \tau_{SMB,MW}(\lambda) (Fig. 2b), and (2) a single-dust model, that is, only carbon dust, which for a shell is
where $R$ is the distance of the cool dense shell (CDS) from the supernova and $\kappa_{\text{col}}(\lambda, \theta)$ is the mass absorption coefficient, in this case, for amorphous carbon. We calculate a grid of models varying the slope $z$ between 0.5 and 4.5, and the lower and upper limits of the grain size distribution, $a_{\text{min}}$ and $a_{\text{max}}$, between 0.001 \(\mu\)m and 5.0 \(\mu\)m. The dispersion of the normalized data (between days 66 and 239) is added to the error (Fig. 2c). We used the chi-square ($\chi^2$) minimization method to determine the best-fitting parameters $z$ and $a_{\text{min}}$ and $a_{\text{max}}$ for all models. The best-fitting model is characterized by $z = 3.6, a_{\text{min}} = 0.001 \mu\text{m}$, and $a_{\text{max}} = 4.2 \mu\text{m}$. However, our models cannot account for the upturn in the light curves, which we attribute to a systematic effect caused by intrinsic line changes rather than to small grains. We note that the considered grain radius is truncated at 5 \(\mu\)m, beyond which the size parameter is $x = 2\alpha/\tau$ becomes prohibitively large, making mass absorption coefficient calculations difficult.

**Light curves.** In Extended Data Fig. 7a we show synthetic UVBRi optical and JHK NIR light curves generated from our X-shooter spectra compared to broad-band photometry from the literature (we have added 1.4 mag to the published U-band magnitude, which happens to be twice the U-band AB offset). It is evident that there is good agreement between them, giving credence to the flux calibration of our spectra. The energy input (Extended Data Fig. 7b) from 66 to 239 days was normalized to the total observed luminosity on about day 26, and the $44Ti$ contribution was subtracted to determine the best-fitting parameters $z$ and $a_{\text{min}}$ and $a_{\text{max}}$ between 0.5 and 4.5, and the lower and upper limits of the grain size distribution, for fixed $a_{\text{min}} = 0.001 \mu\text{m}$ (Fig. 3). The $\chi^2$ value for a desired confidence limit $p$ is calculated as $\chi^2 = \chi^2_{\text{min}} + \Delta\chi^2(p)$, where $\chi^2_{\text{min}}$ is the global minimum $\chi^2$ value of all models. The best-fitting model is characterized by $z = 3.6, a_{\text{min}} = 0.001 \mu\text{m}$, and $a_{\text{max}} = 4.2 \mu\text{m}$. However, our models cannot account for the upturn in the light curves, which we attribute to a systematic effect caused by intrinsic line changes rather than to small grains. We note that the considered grain radius is truncated at 5 \(\mu\)m, beyond which the size parameter is $x = 2\alpha/\tau$ becomes prohibitively large, making mass absorption coefficient calculations difficult.

**Dust heating and vaporization.** A dust grain of radius $a$ located at a distance $R$ from the supernova will attain an equilibrium temperature $T_{\text{eq}}$, determined by the balance between the rate it is heated by the supernova and its cooling rate by NIR emission. The equation describing this balance is given by:

$$
\int_0^\infty Q_{\text{abs}}(\lambda, a) \left(\frac{L_{\lambda}(\lambda)}{4\pi R^2}\right) d\lambda = \int_0^\infty 4\pi a^2 Q_{\text{abs}}(\lambda, a)\tau_{\text{em}}(\lambda, T_{\text{dust}}) d\lambda
$$

The supernova will vaporize a grain when its temperature exceeds the vaporization temperature. We take $T_{\text{vap}} \approx 1,500 \text{K}$ for silicates. Owing to the large uncertainty in $T_{\text{vap}}$, we adopt a temperature range of 2,000–3,000 K.

The supernova light is preceded by a short (\(\Delta t \approx 1\) d) burst of radiation as the shock, resulting from the core collapse, breaks out of the stellar surface. From direct observations of such a shock breakout and models to fit early ultra-violet optical light curves, a shock breakout burst typically lasts around 100 s to 1,000 s after maximum, varying from 3.5 to 10 km s$^{-1}$ for small (that is, favouring large grains). For small grains the $\alpha$ is almost independent of $x$. For large $x$ the dust mass remains independent of $\alpha$ for large grains, whereas for small $x$ the dust mass increases steeply with increasing $a_{\text{min}}$.

Requiring that the extinction and emission dust mass originate from the CDS, the dust mass is derived from either the extinction or the NIR emission. The allowed location of the CDS is constrained by $R_{\text{CDS}} \approx R_{\text{shock}}$ (Extended Data Fig. 9b). The location of the forward shock $R_{\text{shock}}$ at day 239 is estimated assuming a velocity of 3.5 to 10 km s$^{-1}$ until 26 days past peak and 3,000 km s$^{-1}$ for the subsequent 213 days.

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Extended Data Figure 1 | Time sequence of the supernova spectra. Spectra (flux density (Jy)) from ten epochs between \( t = 26 \) days and 868 days past peak. The spectra are offset by an arbitrary constant. The atmospheric telluric bands at 1.33–1.43 \( \mu \)m and 1.79–1.96 \( \mu \)m have been excluded, as well as the dichroic gaps between the X-shooter instrument arms at 0.54–0.56 \( \mu \)m and 0.97–0.995 \( \mu \)m. The light-grey spectrum is an interpolated spectrum at the epoch of observations of the Infrared Array Camera 3.6 \( \mu \)m and 4.5 \( \mu \)m data (grey stars)\(^{11}\). The solid grey curves are fits to the spectra, composed of multiple distinct black-body functions.
Extended Data Figure 2 | NIR excess dust emission in supernova spectra at three different epochs. The spectral shape of the supernova (SN) shows little evolution for the early epochs (44 and 196 days past peak). The late epoch at 868 days exhibits strong NIR emission while the supernova continuum has faded. The atmospheric telluric bands at 1.33–1.43 μm and 1.79–1.96 μm, as well as the dichroic gaps of the X-shooter instrument arms at 0.54–0.56 μm and 0.97–0.995 μm, have been excluded.
Extended Data Figure 3 | Line profiles.  

**a**, Comparison of the observed line profile (left panel) to the line profile of the Lorentzian line fits (right panel), illustrated for H$\beta$ $\lambda$4,861.35.  

**b**, The left panel shows the line profile of the H$\alpha$ $\lambda$6,562.79 line. The progressive broadening of the line causes both the blue and red wings to cross at different epochs. The right panel shows the line profile of the He I $\lambda$5,875.621 line exhibiting a similar effect. The lines increasingly deviate from a Lorentzian profile.
Extended Data Figure 4 | Development of the broad P Cygni profile of Hβ.

Within the early epochs (<239 days) the hydrogen emission line $\text{H} \beta$ develops a strong P Cygni profile. The minimum of the P Cygni profile is at about 7,500 km s$^{-1}$. The largest velocities associated with the P Cygni profile are at about 20,000 km s$^{-1}$. The late epoch (868 days) has been scaled by a factor of ten and offset for better comparison to the early epochs. The Hβ line no longer exhibits features of high velocities. The wings of the intermediate-velocity component extend to around 2,000–3,000 km s$^{-1}$. 

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Extended Data Figure 5 | Velocity components and asymmetry of the intermediate emission lines. a, The left panel shows that the Hα λ6,562.79 line cannot be fitted with a single Lorentzian (purple solid curve). The right panel shows the broad (pink dotted curve) and the intermediate-velocity component (purple dotted curve) and the combination of the two (blue solid curve). b, The Hβ λ4,861.35 line is asymmetric with respect to its peak velocities (approximately −458 km s⁻¹ at 140 days and approximately −768 km s⁻¹ at 239 days). The mirrored emission lines are shown as thin purple curves. The mirror axis is shown as a black dashed-dotted curve. Similar effects are seen for other emission lines.
Extended Data Figure 6 | Evolution of the blueshift velocity of hydrogen and metal lines. The blueshift of the hydrogen lines is wavelength-dependent and increases with time for the early epochs. At any epoch the blueshift is smaller for lines at longer wavelengths. The filled symbols correspond to the blueshifts of the hydrogen emission lines and the open circles correspond to the oxygen lines. The blueshift-to-HWHM ratio for the early epochs resembles the extinction curves (Fig. 2).
Extended Data Figure 7 | Light curves. a, Synthetic UVBRI and JHK light curves (filled circles) compared to the UBVRI optical photometry of ref. 12 (small stars). b, Energy output. The temporal evolution of the UVO and NIR luminosities (blue and red symbols, respectively) and the total bolometric (UVO + NIR) luminosity (black diamonds). The green curve is a $t^{-0.4}$ power-law approximation to the UVO emission at early times. We have included data points from the literature (filled stars) at 553 days (ref. 12). The maximum possible contributions to the heating of the ejecta from the radioactively decaying $^{56}$Co and the isotope $^{44}$Ti are shown as a dotted curve and a dashed line, respectively.
Extended Data Figure 8 | Dust vaporization radii and temperatures as a function of grain radius. 

a, Radii $R_{\text{cav}}$, from an initial burst of radiation.

b, Radii $R_{\text{vap}}$, from the observed supernova luminosity at 26 days. $R_{\text{cav}}$ and $R_{\text{vap}}$ depend on the vaporization temperatures $T_{\text{vap,AC}}$ and $T_{\text{vap,Si}}$. The black line indicates the location, $R_{\text{CDS}}$, of the CDS.

c, The dust temperatures at $R_{\text{CDS}}$, for grains heated by the supernova light and cooled through the NIR emission. The dashed line indicates $T_{\text{vap}}$ derived from the spectral fits (26 days). Amorphous carbon grains (solid curve) have temperatures $\leq T_{\text{vap,AC}}$. Silicate grains (dotted curve) would be hotter than $T_{\text{vap,Si}}$ and therefore cannot exist.
Extended Data Figure 9 | Dust mass at 239 days past peak. a, Sensitivity of the dust mass to the parameters $a_{\text{max}}$ (coloured curves) and $\sigma$ of the grain-size distribution function. The filled coloured squares represent the dust masses for the parameters of the grain size distribution function of the 1σ (red), 2σ (orange) and 3σ (blue) confidence intervals (Figs 2c and 3). b, The extinction dust mass and its standard deviation (green-shaded band), the dust mass from the NIR emission (red-shaded band) and the radius range $R_{\text{vap}} \leq R_{\text{CDS}} \leq R_{\text{shock}}$ (blue lines and shaded area). The overlapping region (purple framed area) of the three bands constrains the radius of the CDS ($R_{\text{CDS}}$) and the dust mass.
Extended Data Table 1 | Log of the VLT/X-shooter observations of SN 2010jl

| Date (UT)   | Airmass | Seeing (") | Exposure times (s) | Days past peak on 2010 Oct 18.6 UT |
|-------------|---------|------------|--------------------|-----------------------------------|
|             |         |            | UVB    | VIS    | NIR    |                    |
| 2010 Nov 13.4 | 1.53    | 0.91       | 2×100  | 2×100  | 2×100  | 26                 |
| 2010 Dec 1.4  | 1.25    | 1.74       | 2×250  | 2×250  | 8×100  | 44                 |
| 2010 Dec 23.3 | 1.22    | 1.52       | 2×250  | 2×250  | 8×100  | 66                 |
| 2011 Jan 30.3 | 1.21    | 1.05       | 2×250  | 2×250  | 8×100  | 104                |
| 2011 Feb 16.1 | 1.34    | 0.87       | 2×250  | 2×250  | 8×100  | 121                |
| 2011 Mar 7.2  | 1.24    | 0.77       | 2×250  | 2×250  | 8×100  | 140                |
| 2011 Mar 25.1 | 1.21    | 0.98       | 2×400  | 2×450  | 10×100 | 158                |
| 2011 May 3.0  | 1.21    | 0.74       | 2×400  | 2×450  | 10×100 | 196                |
| 2011 Jun 15.0 | 1.81    | 0.90       | 4×550  | 4×600  | 32×100 | 239                |
| 2013 Mar 4.0  | 1.28    | 0.86       | 8×698  | 8×605  | 56×100 | 868                |