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Supernova SN 2011fe from an exploding carbon–oxygen white dwarf star

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Type Ia supernovae have been used empirically as 'standard candles' to demonstrate the acceleration of the expansion of the Universe[1–3] even though fundamental details, such as the nature of their progenitor systems and how the stars explode, remain a mystery[4–6]. There is consensus that a white dwarf star explodes after accreting matter in a binary system, but the secondary body could be anything from a main-sequence star to a red giant, or even another white dwarf. This uncertainty stems from the fact that no recent type Ia supernova has been discovered close enough to Earth to detect the stars before explosion. Here we report early observations of supernova SN 2011fe in the galaxy M101 at a distance[7] from Earth of 6.4 megaparsecs. We find that the exploding star was probably a carbon–oxygen white dwarf, and from the lack of an early shock we conclude that the companion was probably a main-sequence star. Early spectroscopy shows high-velocity oxygen that slows rapidly, on a timescale of hours, and extensive mixing of newly synthesized intermediate-mass elements in the outermost layers of the supernova. A companion paper[8] uses pre-explosion images to rule out luminous red giants and most helium stars as companions to the progenitor.

Supernova 2011fe was detected in the Pinwheel galaxy (M101; Fig. 1) on 2011 August 24.167 (03:59 UT) with a g-band magnitude of 17.35 mag by the Palomar Transient Factory (PTF). Observations on the previous night revealed no source to a limiting magnitude of 21.5 mag. Given the distance to M101 of 6.4 Mpc (ref. 7), this first observation identified the supernova at an absolute magnitude of −11.7, roughly 1/1,000 of its peak brightness.

Following an alert sent to the PTF consortium (at 19:51 UT), observations were immediately undertaken by NASA's Swift satellite, and spectroscopic observations were carried out at 20:42 UT on the robotic Liverpool Telescope (La Palma, Canary Islands) equipped with the FRODOSpec spectrograph. After the calibration of this spectrum, at 23:47 UT an Astronomer's Telegram was issued[9] identifying SN 2011fe as a young supernova of type Ia. Eight hours later, a low-resolution spectrum was obtained with the Kast spectrograph at the Lick 3-m Shane telescope (Mt Hamilton, California) and a high-resolution spectrum was obtained with the HIRES spectrograph at the Keck I telescope (Mauna Kea, Hawaii). These spectra are presented in Fig. 2 (Supplementary Information).

The discovery and extensive follow-up photometry allow us to estimate the time of explosion to high precision (Fig. 3). At very early times, the luminosity should scale as the surface area of the expanding fireball and thus is expected to increase as t^2, where t is the time since the explosion. This assumes that neither the photospheric temperature nor the velocity changes significantly and that the input energy from the radioactive decay of ^{56}Ni to ^{56}Co is relatively constant over this period and occurs near the photosphere. Observations by Swift show only small changes in the relative flux between the optical and ultraviolet spectral ranges, and the velocity evolution over the first 24 h is small—consistent with these assumptions (Supplementary Information).

Using this 't^2 model', we find an explosion time at modified Julian date (MJD) 55796.696 ± 0.003 (Fig. 3). Letting the exponent of the power law differ from two, which captures some of the deviations from the fireball model, and fitting just the first three nights of data, results in a best-fit explosion date of MJD 55796.687 ± 0.014 (2011 August 23, 16:29 ± 20 min UT). The exponent of the power law is 2.01 ± 0.01,

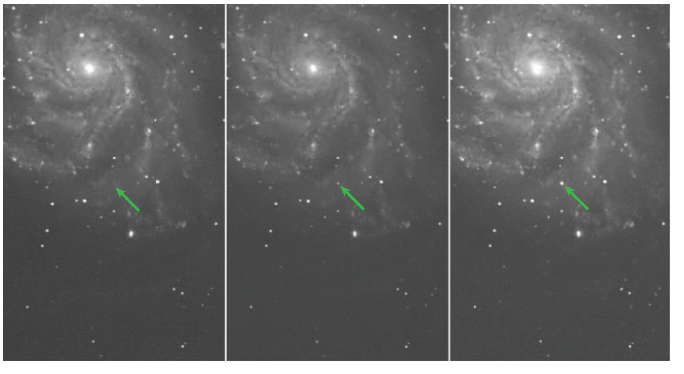

Figure 1 | PTF g-band image sequence of the field of M101 showing the appearance of SN 2011fe. From left to right, images are from August 23.22, 24.17 and 25.16 UT. The supernova was not detected on the first night to a 3σ limiting magnitude of 21.5 mag, was discovered at magnitude 17.35 mag and increased by a factor of ten in brightness to 14.86 mag the following night. The supernova peaked at magnitude ~9.9 mag, making it the fifth-brightest supernova in the past century. The PTF is a wide-field optical experiment designed to explore the variable sky systematically on a variety of timescales, with one particular focus being the very early detection of supernovae[22,23]. Discoveries such as this one have been made possible by coupling real-time computational tools to extensive astronomical follow-up observations[24,25].

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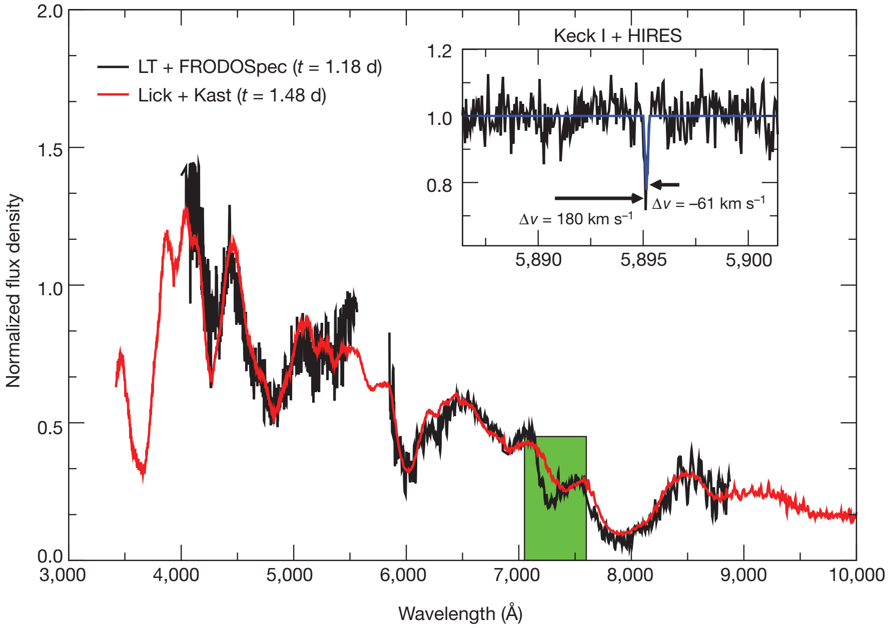

Figure 2 | Spectra of SN 2011fe taken 1.5 d after the explosion. Ions typical of pre-maximum type Ia supernovae are seen: O I, Mg II, Si II, S II, Ca II and Fe II are present at photospheric velocities of 16,000 km s^{-1}. In addition, the fit shows the presence of C II at wavelengths of $\lambda = 6{,}580$ and 7,234 Å. Both high-velocity Si II and Ca II are seen (with velocities exceeding 21,000 km s^{-1}), as is high-velocity O I (green highlighted region), the first evidence of such a feature in a type Ia supernova. This feature evolves in ~8 h, between the measurements of the first two low-resolution spectra. LT, Liverpool Telescope. Inset, Keck I + HIRES spectrum centred on the Na I D line. In this wavelength range, we identify only a single significant absorption feature. Fitting a Gaussian profile to it (blue line), we measure a central wavelength of $\lambda = 5{,}893.75 \pm 0.02$ Å and a full-width at half-maximum intensity of 0.184 ± 0.009 Å. The inferred line equivalent width is $W = 0.045 \pm 0.009$ Å. If we associate this feature with Na I at $\lambda = 5{,}889.95$ Å (the stronger of the two components in the Na I doublet), the observed wavelength is offset from the rest wavelength by $\Delta v = c(\lambda_{obs}/\lambda_{rest} - 1) = 180$ km s^{-1} (where c denotes the speed of light). Similarly, the line is blueshifted from the systemic velocity of M101 ($v = 241 \pm 2$ km s^{-1}; ref. 26) by $\Delta v_{M101} = -61$ km s^{-1}. Given the high galactic latitude ($b = 59.8°$), we consider it likely that the absorbing material originates in M101 and that the total extinction to the supernova is negligible.

consistent with the model discussed above. On the basis of these fits, our first data points were obtained just over 11 h after SN 2011fe exploded.

We analysed the Lick spectrum of SN 2011fe using the automated supernova spectrum interpretation code SYNAPPS[10] (Supplementary Information). At this time only a few hundredths of a solar mass of material are visible above the photosphere, yet ions typical[11] of pre-maximum type Ia supernovae are seen: O I, Mg II, Si II, S II, Ca II and Fe II are present with velocities of 16,000 km s^{-1}. The fit also shows the presence of C II at rest wavelengths of $\lambda = 6{,}580$ and 7,234 Å. Iron III was not needed in the fit. Both high-velocity Si II and Ca II are confirmed by SYNAPPS (with velocities surpassing 21,000 km s^{-1}). Notably, SYNAPPS finds high-velocity O I (velocity in excess of 20,000 km s^{-1}) for the absorption centred at 7,400 Å. This feature evolved significantly in only 8 h, between the times at which data was taken at the Liverpool Telescope and the Lick telescope, with the minimum of the O I absorption slowing from 18,000 to 14,000 km s^{-1}. The rapid evolution in these optically thin layers is best explained in terms of geometrical dilution during the early phases. To our knowledge, this is the first identification of rapidly evolving high-velocity oxygen in the ejecta of a type Ia supernova.

The early-time spectra provide fundamental insight into the explosion physics of this supernova. As in previous[12] type Ia supernovae, intermediate-mass elements dominate the spectrum. In addition, we see strong features from unburnt material (carbon and high-velocity oxygen). The overlap in velocity space implies that the explosion processed the outer layers of the progenitor white dwarf but left behind (at least some) carbon and oxygen. The unburnt material could be confined to pockets, or the ejecta in the outer layers may be thoroughly mixed. The doubly ionized species (for example Si III and Fe III), which are often seen in the spectra of many early and maximum-light type Ia supernovae[13,14], are absent even though our observations were made ~1 d after the explosion, when the energy input from radioactive decay is near its peak. Supernova 2011fe is spectroscopically most similar to the slightly underluminous type Ia SN 1992A and SN 1994D[15,16], the second of which also has high-velocity features in the −12-d spectrum[17]. One potential explanation for this is that although some ^{56}Ni has been mixed out to the photosphere, the majority produced in

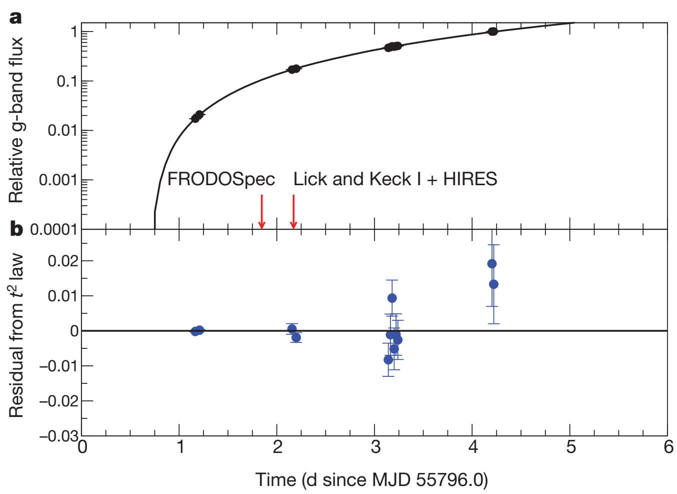

Figure 3 | Early photometry of SN 2011fe shows a parabolic rise and constrains the time of explosion. a, Relative g-band flux as a function of time for the first four nights after detection. Here we have fit the rise with a t^2 fireball model: we assume that the flux is proportional to $(t - t_{expl})^2$, where t_{expl} denotes the time of explosion. **b**, Residuals from the fit. By letting the exponent differ from two, allowing for a potential departure from the fireball model and only fitting the first three nights of data, we find a best-fit explosion date of August 23.687 ± 0.014 UT. On the basis of these fits, our first data points were obtained just over 11 h after SN 2011fe exploded. Error bars, 1σ.

the explosion is confined to the innermost layers of the atmosphere and the bulk of the heating is thus well separated from the portion of the atmosphere we view in these spectra.

The early detection of SN 2011fe allows us to put considerable constraints on the progenitor system of this type Ia supernova. At early times (about 1 d or less after explosion), radiative diffusion from the shock-heated outer layers of the ejecta is a contributor to the supernova luminosity. The shock can originate either in the detonation of the white dwarf[18] or in a later collision with the companion star[19]. Dimensionally, the shock luminosity in this cooling, expanding envelope phase is $L \propto E(t)/t_d$, where $E(t)$ is the ejecta internal energy at the elapsed time, t, and t_d is the effective diffusion time through the homologously expanding remnant. Because the ejecta in these phases are heavily radiation dominated, the internal energy decreases during adiabatic expansion as $E(t) \propto R_0/vt$, where R_0 is the initial radius of the star and v is the velocity of the ejecta. Thus, the early-time luminosity is proportional to R_0 and the effective temperature, $T_{\rm eff}$, is proportional to $L^{1/4} \propto R_0^{1/4}$ (Supplementary Information).

Although there must be radioactive heating in the outer layers of the supernova, we can make the very conservative upper-limit approximation that the earliest g-band photometric point ($L \approx 10^{40}$ erg s^{-1} at $\sim$0.5 d) is entirely due to the explosion. We then infer an upper limit to the radius of the progenitor star, $R_0 < 0.1 R_\odot$ (Fig. 4), where $R_\odot$ is the solar radius. This provides compelling, direct evidence that the progenitor of SN 2011fe was a compact star, namely a white dwarf. When we add the early carbon and oxygen observations, we conclude that the progenitor must have been a carbon–oxygen white dwarf.

The early-time light curve also constrains the properties of a binary star system[19], because the collision of the supernova with a companion star will shock and reheat a portion of the ejecta. The resulting luminosity is proportional to the separation distance, a, between the stars, and will be most prominent for observers aligned with the symmetry axis. If the companion were a red giant, the early luminosity would be several orders of magnitude greater than that observed, and this possibility can be ruled out regardless of the viewing angle. A main-sequence companion is compatible with the data, unless SN 2011fe happened to be seen on-axis (within $\sim$40° of the symmetry axis), in which case the luminosity at 0.5 d rules out any binary with $a \leq 0.1 R_\odot$. Despite this caveat, we conclude that the companion is most likely to be a main-sequence star.

Recent simulations of double-degenerate mergers have found that some material from the disrupted secondary white dwarf may get pushed out to large radius (10^{13}–10^{14} cm), either in the dynamics of the merger[20] or in the subsequent long-term thermal evolution of the system[21]. The interaction of the ejecta with this roughly spherical medium should produce (for all viewing angles) bright, early ultraviolet–optical emission, in conflict with what is observed. Our restriction that the dense circumstellar medium must reside at a radius of $\leq 10^{10}$ cm thus presents a tight constraint for merger models, and only a few of those proposed so far may be applicable to this supernova[6].

We caution that the conclusions we have come to regarding SN 2011fe rely on a theoretical interpretation. A companion paper[8] uses independent methodology to place direct observational limits on the companion star from historical imaging $\sim$100 times deeper in absolute luminosity than previous attempts using other type Ia supernovae.

These results come from only the first week or so of observation of SN 2011fe. Being the first close type Ia supernova to be detected in the era of modern instrumentation, SN 2011fe will undoubtedly become the best-recorded thermonuclear supernova in history, and will be studied daily across the spectral range from the ultraviolet to the infrared well into the faint nebular phase. As such, it will form the foundation on which our knowledge of more distant type Ia supernovae is built.

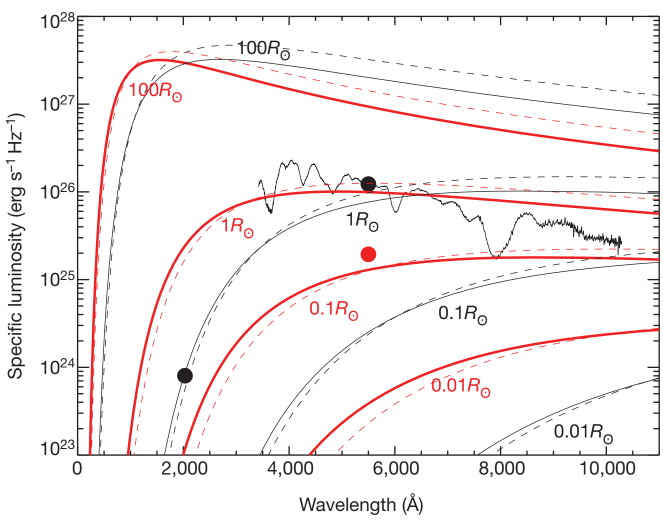

Figure 4 | Models and early data limit the radius of the exploding star of SN 2011fe. The thick red lines show black-body models for the spectrum at 0.5 d assuming different values of the progenitor star radius, R_0. The solid lines and the dashed lines are derived from two separate analyses[19,27]. The observed g-band photometry point at this time (red circle) constrains the radius of the progenitor star (or the surrounding opaque circumstellar medium) to be $\leq 10^{10}$ cm $\approx 0.1 R_\odot$. The black spectrum and circles show corresponding model predictions (circles) and observations (spectrum) at 1.45 d. In all models, we have assumed an ejecta mass equal to the Chandrasekhar mass, an explosion energy of 10^{51} erg and an opacity of 0.2 cm^2 g^{-1}, appropriate for electron scattering in a singly ionized medium with a mass number/atomic number ratio of two. The early-time data indicate that the progenitor of SN 2011fe was a compact star, namely a white dwarf.

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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 P.E.N., M.S. and D.A.H. oversee the PTF programme on type Ia supernovae. P.E.N. oversaw the preparation of the manuscript. M.S., D.B., K.M., Y.-C.P., J.L. and P.J. performed and reduced the FRODOSpec observations. S.B.C., M.T.K., A.V.F. and J.M.S. obtained and reduced the Lick spectrum. G.W.M., A.W.H. and H.T.I. obtained the HIRES observations. S.B.C., J.S.B., S.R.K., M.M.K., N.M.L., E.O.O., R.M.Q. and D.P. assisted in the operation of the Palomar 48-inch telescope as part of the PTF collaboration. R.C.T. and J.E.T. performed the SYNAPPS analysis. D.K., L.B. and P.P. assisted with the theoretical interpretation of our observations. N.S., B.J.F., J.T.P., D.S., F.B.B., B.D., M.L.G., I.M.H., P.M., E.P., E.S.W. and A.G. assisted in follow-up observations of SN 2011fe.

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