LETTER

doi:10.1038/nature11877

An outburst from a massive star 40 days before a supernova explosion

E. O. Ofek[1], M. Sullivan[2,3], S. B. Cenko[4], M. M. Kasliwal[5], A. Gal-Yam[1], S. R. Kulkarni[6], I. Arcavi[1], L. Bildsten[7,8], J. S. Bloom[4,9], A. Horesh[6], D. A. Howell[8,10], A. V. Filippenko[4], R. Laher[11], D. Murray[12], E. Nakar[13], P. E. Nugent[4,9], J. M. Silverman[4,14], N. J. Shaviv[15], J. Surace[11] & O. Yaron[1]

Some observations suggest that very massive stars experience extreme mass-loss episodes shortly before they explode as supernovae[1–4], as do several models[5–7]. Establishing a causal connection between these mass-loss episodes and the final explosion would provide a novel way to study pre-supernova massive-star evolution. Here we report observations of a mass-loss event detected 40 days before the explosion of the type IIn supernova SN 2010mc (also known as PTF 10tel). Our photometric and spectroscopic data suggest that this event is a result of an energetic outburst, radiating at least 6×10^{47} erg of energy and releasing about 10^{-2} solar masses of material at typical velocities of 2,000 km s^{-1}. The temporal proximity of the mass-loss outburst and the supernova explosion implies a causal connection between them. Moreover, we find that the outburst luminosity and velocity are consistent with the predictions of the wave-driven pulsation model[6], and disfavour alternative suggestions[7].

Type IIn supernovae are a diverse class of transient events, spectroscopically defined by narrow and/or intermediate-width hydrogen emission lines (up to a few thousand km s^{-1} wide)[8–10]. These emission lines probably originate from optically thin circumstellar matter ionized by the supernova shock and/or radiation field. The spectra and light curves of these supernovae are interpreted as signatures of interaction between the supernova ejecta and mass that has been expelled before the explosion[11–13]. The most likely detection of a progenitor before its explosion as a type IIn supernova[3] involved a luminous blue variable (LBV)—a class of objects which are known for their vigorous eruptive mass-loss events[14]. Very recently, a massive star in the nearby galaxy NGC 7259, namely SN 2009ip, had a series of outbursts[15–17] with a typical expelled-matter velocity of about 500 km s^{-1}, possibly followed by a supernova event[18,19] exhibiting P Cygni lines with velocities of $\sim10^4$ km s^{-1}. Another event that showed an outburst before its supernova explosion is SN 2006jc, which is further discussed in Supplementary Information section 7.

The Palomar Transient Factory[20,21] (PTF), a ground-based, wide-field survey, discovered the type IIn SN 2010mc[22] in images obtained on 2010 August 20.22 (UTC dates are used throughout this paper). It is located at right ascension 17 h 21 min 30.68 s, declination $+48^\circ\,07'\,47.4''$ (J2000.0), at redshift $z = 0.035$, which corresponds to a luminosity distance of 153 Mpc. Our continuing search for precursor events in pre-explosion images of nearby type IIn supernovae observed by PTF revealed a positive precursor detection for this supernova. Here we measure time relative to 2010 August 20.22, which corresponds to the onset of the supernova explosion (the main event visible in Fig. 1). The initial bump in the pre-supernova light curve emerged at day −37 relative to the supernova discovery date, and peaked at an absolute magnitude of about −15 ($\sim2.25\times10^{41}$ erg s^{-1}) in the $R_{\rm PTF}$ band. The main supernova explosion then brightened for two weeks and peaked at an $R_{\rm PTF}$ absolute magnitude of −18.4 ($\sim5.2\times10^{42}$ erg s^{-1}), radiating a total bolometric luminosity of $\sim3\times10^{49}$ erg, while the precursor bump radiated $\sim6\times10^{47}$ erg (or more, due to the unknown bolometric correction).

Spectra of the supernova, showing a blue continuum with Balmer emission lines, are presented in Fig. 2. The continuum becomes redder

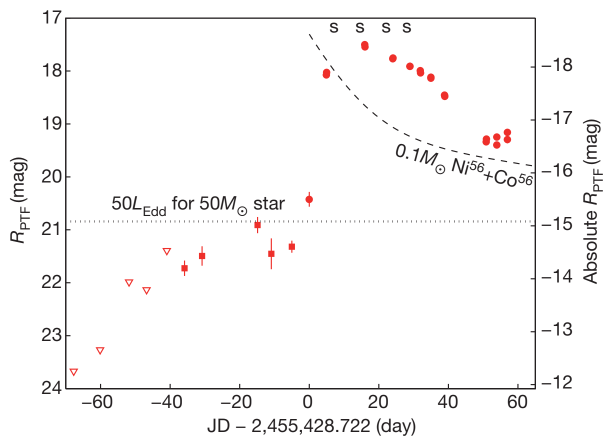

Figure 1 | The light curve of SN 2010mc as obtained with the Palomar 48-inch telescope. Red circles, data based on individual images; squares, based on coadded images; open triangles, 3σ upper limits derived from coadded images. Error bars, 1σ. The object magnitudes are given in the PTF magnitude system[27,28]. The left-hand y axis shows the R-band apparent magnitude; the right-hand y axis indicates the R-band absolute magnitude. Other data sets discussed in the Supplementary Information, including those from the Palomar 60-inch and Swift-UVOT, are listed in Supplementary Table 3. All the photometric and spectroscopic data are available via the WISeREP website[29]. Dashed line at top right, the expected luminosity from the radioactive decay of an ejected mass of 0.1 $M_\odot$ of Ni^{56} (which decays to Co^{56}, which decays to Fe^{56}). Assuming that at late times the optical depth is sufficiently large to convert the radioactive energy to optical luminosity, but not too large so it will go into PdV work, this line represents an upper limit on the total amount of Ni^{56} in the ejecta; it was set to coincide with the latest observation of the supernova at Julian date JD ≈ 2,455,758 (see Supplementary Table 3). The dotted line represents a bolometric luminosity equal to 50 times the Eddington luminosity $L_{\rm Edd}$ for a 50 $M_\odot$ star (order of magnitude estimate of the mass of the progenitor assuming it is a massive star). The right edges of the "S" symbols above the light curve indicate the epochs at which we obtained spectra (see Fig. 2). A full version of this light curve, including the late-time observations, is shown in Supplementary Information.

[1]Benoziyo Center for Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel. [2]School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK. [3]Department of Physics (Astrophysics), University of Oxford, Keble Road, Oxford OX1 3RH, UK. [4]Department of Astronomy, University of California, Berkeley, California 94720-3411, USA. [5]Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, California 91101, USA. [6]Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, California 91125, USA. [7]Kavli Institute for Theoretical Physics, Kohn Hall, University of California, Santa Barbara, California 93106, USA. [8]Department of Physics, Broida Hall, University of California, Santa Barbara, California 93106, USA. [9]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA. [10]Las Cumbres Observatory Global Telescope Network, 6740 Cortona Drive, Suite 102, Goleta, California 93117, USA. [11]Spitzer Science Center, California Institute of Technology, M/S 314-6, Pasadena, California 91125, USA. [12]Physics Department, University of Wisconsin–Milwaukee, Milwaukee, Wisconsin 53211, USA. [13]School of Physics and Astronomy, Tel-Aviv University, 69978 Tel-Aviv, Israel. [14]Department of Astronomy, University of Texas, Austin, Texas 78712-0259, USA. [15]Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel.

with time, and its slope corresponds to an effective temperature of more than 16,000 K at day five, dropping to about 8,000 K at day 27. The Hα line has an initial width of $\sim 3 \times 10^3$ km s^{-1} at day 6, decreasing to $\sim 10^3$ km s^{-1} at day 14. A broad (10^4 km s^{-1}) P Cygni profile emerges by day 27. The spectra also show He I lines with decreasing strength, presumably due to the drop in temperature.

The nature of the precursor bump is very intriguing and can potentially tell us a great deal about the supernova explosion and the progenitor. The only interpretation that is fully consistent with the photometric and spectroscopic evidence is that the first bump represents an outburst from the SN progenitor about one month before explosion, while the brighter bump is initiated by a full explosion of the star a few weeks later. Below we analyse this model in the context of the photometric and spectroscopic data. In Supplementary Information section 6, we discuss some alternative models and conclude that they are unlikely.

The mass ejected by the precursor burst can be estimated in various independent ways. By requiring that the precursor integrated bolometric luminosity, $E_{\mathrm{bol,prec}}$, be lower than the kinetic energy of the precursor outburst (moving at velocity v_{prec}, in km s^{-1}) which powers it, we can set a lower limit on the mass ejected in the precursor outburst, $M_{\mathrm{prec}} \gtrsim 2E_{\mathrm{bol,prec}} v_{\mathrm{prec}}^{-2} \approx 1.5 \times 10^{-2} (v_{\mathrm{prec}}/2{,}000)^{-2} M_{\odot}$. The outburst velocity is estimated from the line widths of 1,000–3,000 km s^{-1}, seen in the early-time spectra of the supernova. As this mass was presumably ejected over a period of about one month (that is, the outburst duration), the effective annual mass-loss rate is about 10 times higher. A similar order-of-magnitude argument can be used to put an upper limit on the mass in the precursor outburst. If some of the supernova bolometric energy, $E_{\mathrm{bol,SN}}$, is due to interaction between the supernova ejecta, moving at v_{SN} (in km s^{-1}), and the precursor shell, and assuming high efficiency of conversion of the kinetic energy to luminosity, then $M_{\mathrm{prec}} \lesssim 2E_{\mathrm{bol,SN}} v_{\mathrm{SN}}^{-2} \approx 3 \times 10^{-2} (v_{\mathrm{SN}}/10^4)^{-2} M_{\odot}$.

Another method to estimate the mass in the ejecta is based on the Hα emission-line luminosity and the radius of the photosphere, which is determined from a black-body fit to the spectra (Supplementary Fig. 2). This method, derived in Supplementary Information section 2, suggests a mass-loss rate of $\gtrsim 10^{-1}$ M$_{\odot}$ yr^{-1}, or a total ejected mass of $\gtrsim 10^{-2}$ M$_{\odot}$, if we assume a month-long outburst in which material is ejected at a velocity of 2,000 km s^{-1}.

Another independent method for estimating the mass in the circumstellar matter is based on the rise time of the supernova. Because photons diffuse through material between the supernova and the observer, the supernova rise time gives us an upper limit on the diffusion timescale and therefore the total intervening mass. As the supernova rise time was about one week, this argument suggests that if the shell is spherically symmetric its total mass cannot exceed about 0.4M$_{\odot}$ (see Supplementary Information section 5). Therefore, the kinetic-energy arguments, the Hα luminosity and the diffusion timescale are consistent with each other (and with the X-ray limits derived in Supplementary Information section 3), and indicate that the total mass lost during the outburst is of the order of $\sim 10^{-2}$ M$_{\odot}$.

Our model for the sequence of events is presented in Fig. 3. In a nutshell, this model suggests that the precursor outburst ejected $\sim 10^{-2}$ M$_{\odot}$ at a velocity of 2,000 km s^{-1} about one month before the supernova explosion. Shortly after the supernova explosion, this ejected material was engulfed by the supernova ejecta. At later times, after the optical depth decreases, we start seeing indications of the high velocity of the supernova ejecta. We discuss some less likely alternative models in Supplementary Information section 6.

A surprising result is the short time between the outburst and the explosion, which is a tiny fraction ($\sim 10^{-8}$) of the lifetime of a massive star. Even if massive stars have multiple mass-loss episodes (with mass loss $\gtrsim 10^{-2}$ M$_{\odot}$) during their lifetime, the number of such episodes cannot exceed $\sim$5,000; otherwise, the mass lost will exceed a typical stellar mass. A conservative estimate shows that so far it might be possible to detect such an outburst in a sample of up to about 20 nearby type IIn supernovae, which have deep pre-explosion observations (see Supplementary Information section 7). Therefore, the probability of observing a random burst one month before the explosion is 0.1%. We conclude that such outbursts are either causally related to, or at least two orders of magnitude more common before, the final stellar explosion.

When considering where such an eruption could originate, one is led to the stellar core, as the binding energy it can liberate by contraction and nuclear reactions is sufficiently large. Because the actual luminosity is most probably neutrino-dominated, the Kelvin–Helmholtz timescale for this contraction could be short enough to explain the precursor's rapid rise in luminosity. However, the energy liberated at the core must reach the envelope. This requires an efficient energy-transport mechanism[6]. There are several proposed mechanisms that predict high mass-loss rates before the final stellar explosion. Recently, it was suggested[6] that in some massive stars the super-Eddington fusion luminosities, shortly before core collapse, could drive convective motions that in turn excite gravity waves that propagate towards the stellar surface. The dissipation of these waves could unbind up to several solar masses of the stellar envelope. Alternatively, it was suggested[7] that the mass loss is driven by a common-envelope phase[23] due to the spiralling-in of a neutron star into a giant companion core (a so-called Thorne-Żytkow object), unbinding the companion envelope and setting up accretion onto the neutron star that collapses into a black hole and triggers a supernova explosion shortly thereafter. This model, however, predicts an outflow velocity that is considerably lower than the one observed in the precursor of SN 2010mc, and is therefore disfavoured. Another possible mechanism is the pulsational pair instability supernova[24]. However, current models predict that the mass ejected in these events will probably be much larger than the 10^{-2}M$_{\odot}$ seen in SN 2010mc[5,25].

The velocity and energetics of the precursor of SN 2010mc are consistent with the predictions of the wave-driven outburst mechanism[6]. However, a more detailed theoretical investigation is required in order to test whether this model is consistent with all the observational evidence. In Supplementary Information section 8, given the observed precursor luminosity, we theoretically derive the mass loss (using the wave-driven outburst mechanism) to be ~ 0.05M$_{\odot}$, in excellent agreement with

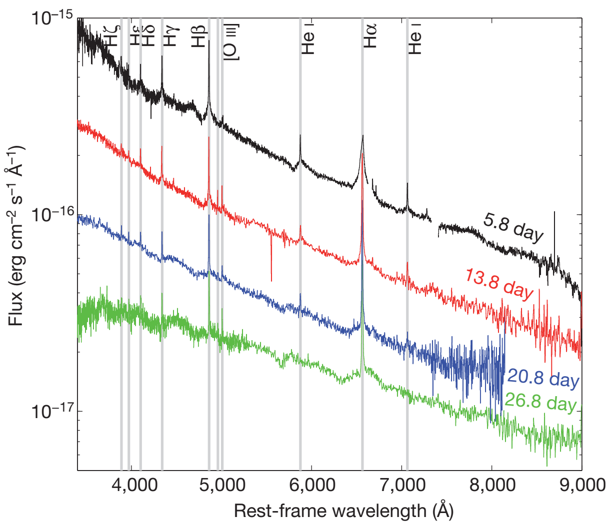

Figure 2 | Spectra of SN 2010mc, showing prominent Balmer emission lines. The early-time spectra are well fitted by a narrow component ($\sim 10^2$ km s^{-1}; the fit includes the instrumental line broadening) and a broad component extending to $\sim 3 \times 10^3$ km s^{-1} at the first epoch, and decreasing to 10^3 km s^{-1} at the second epoch. At later epochs the Balmer Hα line develops a P Cygni profile (similar to that of normal type II supernovae) with a velocity difference between the absorption bottom and the emission peak of $\sim 10^4$ km s^{-1}. At the first epochs we also detect He I lines, some of which are marked on the plot. They become weaker (see Supplementary Fig. 2) at later epochs, presumably owing to the decrease in the effective temperature (Supplementary Fig. 2). This, as well as the absence of He II lines, indicates that our temperature estimate (Supplementary Fig. 2) is reasonable.

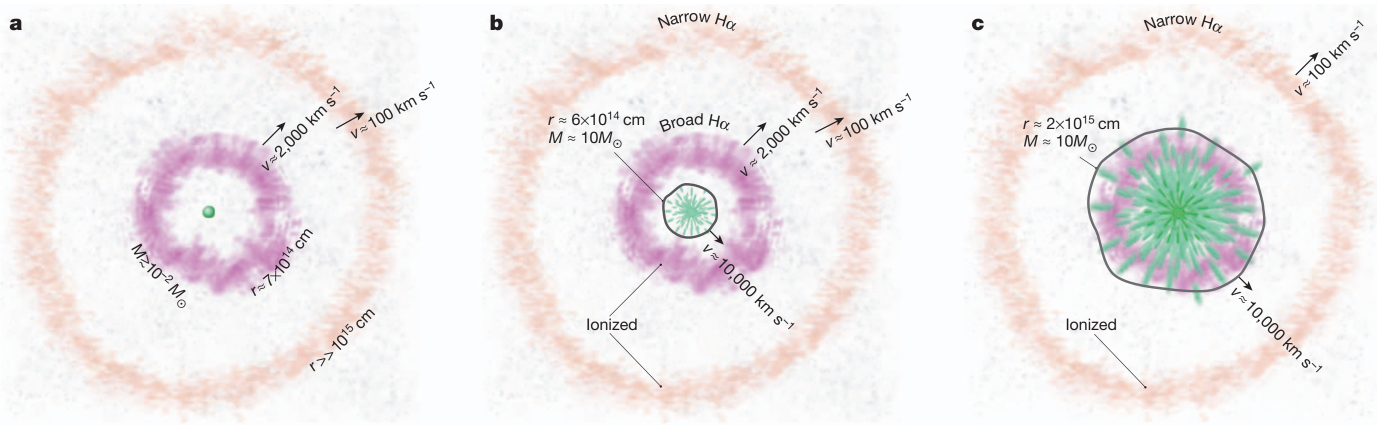

Figure 3 | Qualitative sketch of the proposed model for SN 2010mc. **a**, At day ~0 (relative to the supernova explosion time), an inner shell (purple) with a mass of $\sim 10^{-2}\ M_\odot$, ejected about one month earlier during the precursor outburst and moving at velocity v of about 2,000 km s^{-1}, is located at a radius r of $\sim 7\times10^{14}$ cm. An outer shell (orange), found at a large radius and moving at about 100 km s^{-1} (up to 10^3 km s^{-1}), was ejected at earlier times. This indicates that the progenitor probably had multiple mass-loss episodes in the past tens to hundreds of years before the explosion. **b**, At day ~5, the supernova shock front (dark grey line) moving at ~10,000 km s^{-1} is ionizing the inner and outer shells which produce the broad and narrow Hα emission seen in the early-time spectra. **c**, At day ~20, the supernova shock engulfs the inner shell, and the intermediate-width (~2,000 km s^{-1}) component of the Hα line disappears. Instead we detect a 1,000 km s^{-1} line, presumably due to material ejected during previous, but probably recent, mass-loss episodes and that is found at larger distances from the supernova. We note that inspection of the supernova light curve shows that around day 50 there is an indication of a possible rebrightening, perhaps resulting from the supernova ejecta colliding with such additional material ejected at earlier times. At day ~20, the photospheric temperature decreases and it becomes optically thinner, and therefore we begin seeing an Hα P Cygni profile with a velocity of ~10,000 km s^{-1}. This line become even stronger on day 27. This reflects the unshocked ejecta below the interaction zone.

our mass-loss estimates. Furthermore, we note that the velocity of the precursor ejecta is higher than predicted by other models[7]. Finally, we note that the mass-loss velocity in SN 2010mc is considerably higher than the one observed in SN 2009ip[18], although the mass-loss rate was similar[26].

Received 14 October; accepted 18 December 2012.

1. Dopita, M. A., Cohen, M., Schwartz, R. D. & Evans, R. The 1984 supernova in NGC 3169 — evidence for a superwind. *Astrophys. J.* **287,** L69–L71 (1984).
2. Chugai, N. N. & Danziger, I. J. Supernova 1988Z — low-mass ejecta colliding with the clumpy wind. *Mon. Not. R. Astron. Soc.* **268,** 173–180 (1994).
3. Gal-Yam, A. & Leonard, D. C. A massive hypergiant star as the progenitor of the supernova SN 2005gl. *Nature* **458,** 865–867 (2009).
4. Ofek, E. O. *et al.* Supernova PTF 09UJ: a possible shock breakout from a dense circumstellar wind. *Astrophys. J.* **724,** 1396–1401 (2010).
5. Woosley, S. E., Blinnikov, S. & Heger, A. Pulsational pair instability as an explanation for the most luminous supernovae. *Nature* **450,** 390–392 (2007).
6. Quataert, E. & Shiode, J. Wave-driven mass loss in the last year of stellar evolution: setting the stage for the most luminous core-collapse supernovae. *Mon. Not. R. Astron. Soc.* **423,** L92–L96 (2012).
7. Chevalier, R. A. Common envelope evolution leading to supernovae with dense interaction. *Astrophys. J.* **752,** L2 (2012).
8. Schlegel, E. M. A new subclass of Type II supernovae? *Mon. Not. R. Astron. Soc.* **244,** 269–271 (1990).
9. Filippenko, A. V. Optical spectra of supernovae. *Annu. Rev. Astron. Astrophys.* **35,** 309–355 (1997).
10. Kiewe, M. *et al.* Caltech Core-Collapse Project (CCCP) observations of type IIn supernovae: typical properties and implications for their progenitor stars. *Astrophys. J.* **744,** 10 (2012).
11. Chugai, N. N. & Danziger, I. J. A massive circumstellar envelope around the type-IIn supernova 1995G. *Astron. Lett.* **29,** 649–657 (2003).
12. Ofek, E. O. *et al.* SN 2006gy: an extremely luminous supernova in the galaxy NGC 1260. *Astrophys. J.* **659,** L13 (2007).
13. Smith, N. *et al.* SN 2006gy: Discovery of the most luminous supernova ever recorded, powered by the death of an extremely massive star like η Carinae. *Astrophys. J.* **666,** 1116–1128 (2007).
14. Owocki, S. Hot-star mass-loss mechanisms: winds and outbursts. *Astron. Soc. Pacif. Conf. Ser.* **425,** 199–208 (2010).
15. Smith, N. *et al.* Discovery of precursor LBV outbursts in two recent optical transients: the fitfully variable missing links UGC 2773-OT and SN 2009ip. *Astron. J.* **139,** 1451–1467 (2010).
16. Pastorello, A. *et al.* Multiple major outbursts from a restless luminous blue variable in NGC 3432. *Mon. Not. R. Astron. Soc.* **408,** 181–198 (2010).
17. Foley, R. J. *et al.* The diversity of massive star outbursts. I. Observations of SN 2009ip, UGC 2773 OT2009-1, and their progenitors. *Astrophys. J.* **732,** 32 (2011).
18. Mauerhan, J. C. *et al.* The unprecedented third outburst of SN 2009ip: a luminous blue variable becomes a supernova. Preprint at http://arXiv.org/abs/1209.6320 (2012).
19. Prieto, J. L., Brimacombe, J., Drake, A. J. & Howerton, S. The rise of the remarkable type IIn supernova SN 2009ip. Preprint at http://arXiv.org/abs/1210.3347 (2012).
20. Law, N. M. *et al.* The Palomar Transient Factory: system overview, performance, and first results. *Publ. Astron. Soc. Pacif.* **121,** 1395–1408 (2009).
21. Rau, A. *et al.* Exploring the optical transient sky with the Palomar Transient Factory. *Publ. Astron. Soc. Pacif.* **121,** 1334–1351 (2009).
22. Ofek, E. O. *et al.* X-ray emission from supernovae in dense circumstellar matter environments: a search for collisionless shocks. Preprint at http://arXiv.org/abs/1206.0748 (2012).
23. Taam, R. E. & Ricker, P. M. Common envelope evolution. *New Astron. Rev.* **54,** 65–71 (2010).
24. Rakavy, G., Shaviv, G. & Zinamon, Z. Carbon and oxygen burning stars and pre-supernova models. *Astrophys. J.* **150,** 131–162 (1967).
25. Quimby, R. M. *et al.* Hydrogen-poor superluminous stellar explosions. *Nature* **474,** 487–489 (2011).
26. Ofek, E. O. *et al.* SN 2009ip: Constraints on the progenitor mass-loss rate. *Astrophys. J.* (submitted).
27. Ofek, E. O. *et al.* The Palomar Transient Factory photometric calibration. *Publ. Astron. Soc. Pacif.* **124,** 62–73 (2012).
28. Ofek, E. O. *et al.* The Palomar Transient Factory photometric catalog 1.0. *Publ. Astron. Soc. Pacif.* **124,** 854–860 (2012).
29. Yaron, O. & Gal-Yam, A. WISeREP — An interactive supernova data repository. *Publ. Astron. Soc. Pacif.* **124,** 668–681 (2012).

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

Acknowledgements We thank E. Quataert and M. Cantiello for discussions. The VLA is operated by the National Radio Astronomy Observatory, a facility of the US National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc. This paper is based on observations obtained with the Samuel Oschin Telescope as part of the Palomar Transient Factory project. We are grateful for the assistance of the staff at the various observatories where data were obtained. We acknowledge support from the Arye Dissentshik career development chair, the Helen Kimmel Center for Planetary Science, the Israeli Ministry of Science, the Royal Society, the NSF, the Israeli Science Foundation, the German-Israeli Foundation, ERC, the US Department of Energy, Gary and Cynthia Bengier, the Richard and Rhoda Goldman Fund, the Christopher R. Redlich Fund, and the TABASGO Foundation.

Author Contributions E.O.O. initiated the search for precursor outbursts and wrote the paper, M.S. wrote the image-subtraction pipeline, S.B.C. reduced the Swift-UVOT observations, M.M.K. reduced the P60 observations, A.G.-Y. helped with the spectroscopic analysis, L.B., E.N. and N.J.S. contributed to the theoretical interpretation, A.V.F. assisted with the spectroscopy and edited the paper, D.A.H., D.M. and J.M.S. conducted the spectroscopic observations or reductions, O.Y. helped write the paper, and S.R.K., I.A., J.S.B., R.L., P.E.N. and J.S. built the PTF hardware and software infrastructure.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to E.O.O. (eran@astro.caltech.edu).