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

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Some observations suggest that very massive stars experience extreme mass-loss episodes shortly before they explode as supernovae, as do several models. 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^{49} erg of energy and releasing about 10^{-4} 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, and disfavour alternative suggestions.

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). 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. The most likely detection of a progenitor before its explosion as a type IIn supernova involved a luminous blue variable (LBV)—a class of objects which are known for their vigorous eruptive mass-loss events. Very recently, a massive star in the nearby galaxy NGC 7259, namely SN 2009ip, had a series of outbursts, with a typical expelled-matter velocity of about 500 km s^{-1}, possibly followed by a supernova event exhibiting Cyg lines with velocities of about 10^{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 (PTF), a ground-based, wide-field survey, discovered the type IIn SN 2010mc 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° 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 (≈ 2.25 × 10^{41} erg s^{-1}) in the R_{PTF} band. The main supernova explosion then brightened for two weeks and peaked at an R_{PTF} absolute magnitude of ≈ 18.4 (≈ 5.2 × 10^{42} erg s^{-1}), radiating a total bolometric luminosity of ≈ 3 × 10^{49} erg, while the precursor bump radiated ≈ 6 × 10^{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...
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 $3 \times 10^3$ 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, $L_{bol, prec}$, 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, $M_{prec} \geq 2E_{bol, prec}v_{prec}^2 > 1.5 \times 10^{-2} (v_{prec}/2,000)^{-2} M_\odot$. 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, $E_{bol, SN}$, 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 $M_{prec} \leq 2E_{bol, SN}/v_{SN} \approx 3 \times 10^{-1} (v_{SN}/10^5)^{-2} M_\odot$.

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 $\geq 10^{-2} M_\odot$ yr$^{-1}$, or a total ejected mass of $\geq 10^{-2} M_\odot$, 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 0.4$M_\odot$ (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 $\leq 10^{-2} M_\odot$.

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 $\geq 10^{-2} M_\odot$) during their lifetime, the number of such episodes cannot exceed ~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 IIb 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 convection 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. There are several proposed mechanisms that predict high mass-loss rates before the final stellar explosion. Recently, it was suggested 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 that the mass loss is driven by a common-envelope phase due to the spiralling-in of a neutron star into a giant companion core (a so-called Thorn-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. 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.

The velocity and energetics of the precursor of SN 2010mc are consistent with the predictions of the wave-driven outburst mechanism. 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 $\sim 0.05 M_\odot$, in excellent agreement with...
Figure 3 | Qualitative sketch of the proposed model for SN 2010mc. a. At day \(-9\) (relative to the supernova explosion time), an inner shell (purple) with a mass of \(\sim 10^{-2}\ M_\odot\) is ejected about one month earlier during the precursor outburst and moving at velocity \(v\) of about \(2000\ \text{km s}^{-1}\). b. At day \(-5\), the supernova shock front (dark grey line) moving at about \(10,000\ \text{km s}^{-1}\) is ionizing the inner and outer shells which produce the broad and narrow H\(	ext{\alpha}\) emission seen in the early-time spectra. c. At day \(-20\), the supernova shock engulfs the inner shell, and the intermediate-width mass-loss estimates. Furthermore, we note that the velocity of the precursor ejecta is higher than predicted by other models. Finally, we note that the mass-loss velocity in SN 2010mc is considerably higher than the one observed in SN 2009ip, although the mass-loss rate was similar.

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

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