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LETTERS

A massive hypergiant star as the progenitor of the supernova SN 2005gl

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Our understanding of the evolution of massive stars before their final explosions as supernovae is incomplete, from both an observational and a theoretical standpoint. A key missing piece in the supernova puzzle is the difficulty of identifying and studying progenitor stars. In only a single case—that of supernova SN 1987A in the Large Magellanic Cloud—has a star been detected at the supernova location before the explosion, and been subsequently shown to have vanished after the supernova event[1]. The progenitor of SN 1987A was a blue supergiant, which required a rethink of stellar evolution models[2]. The progenitor of supernova SN 2005gl was proposed to be an extremely luminous object[3], but the association was not robustly established (it was not even clear that the putative progenitor was a single luminous star). Here we report that the previously proposed[3] object was indeed the progenitor star of SN 2005gl. This very massive star was likely a luminous blue variable that standard stellar evolution predicts should not have exploded in that state.

On 2007 September 26.7, we used the Hubble Space Telescope (HST) to observe the location of SN 2005gl within its host galaxy NGC 266, in order to confirm or reject that a luminous point source previously identified in pre-explosion images from 1997[3] as being spatially coincident with this supernova was in fact the progenitor star. In the new images, the point source NGC266_LBV 1 is no longer visible (Fig. 1), confirming that it was, indeed, the progenitor of SN 2005gl. Before our observation, the proposal that NGC266_LBV 1 was the progenitor star of SN 2005gl was subject to two major caveats. First, earlier HST images could not rule out the possibility that the point source detected in 1997 was a compact cluster of many stars, with a combined luminosity of the order of 10^6 solar luminosities ($10^6 L_\odot$). Second, the spatial coincidence of the putative single star with SN 2005gl alone did not provide conclusive evidence that the supernova explosion was actually related to the luminous star—the explosion could have been the result of the death of a lower-luminosity star, projected close to NGC266_LBV 1, but undetectable in the 1997 HST images. Our new observations from 2007 (Fig. 1c), which are substantially deeper than those obtained in 1997, show no trace of SN 2005gl, nor of NGC266_LBV 1, to a deep limit: $V > 25.6$ mag at the 3σ confidence level ($V > 25.9$ mag at the 2σ level; Supplementary Information section 2). These new data attend to both caveats noted above, and show that *NGC266_LBV* 1 was a single star and that it indeed vanished following the explosion of SN 2005gl, as is expected for a supernova progenitor star. On the basis of its luminosity, such a star is likely to be an extreme member of the group of luminous blue variable stars (LBVs), which are thought to be very massive ($>50 M_\odot$, where $M_\odot$ is the solar mass) short-lived stars[4].

Our spectral analysis (Fig. 2) reveals signatures for interaction between the supernova ejecta and a mass shell, previously lost from the progenitor star, which is the defining feature of a supernova of type IIn (refs 5, 6). Thus, our recent data prove that the type IIn supernova 2005gl resulted from the explosion of a most luminous, and probably very massive, progenitor star. Following SN 1987A, this is only the second case for which such solid evidence exists, with SN 2005gl being more than 1,000 times more distant than SN 1987A (66 Mpc versus 50 kpc, respectively), and NGC266_LBV 1 being approximately ten times more luminous than Sk −69 202, the blue supergiant progenitor of SN 1987A[1].

During the past decades, several objects detected in pre-explosion images of the locations of nearby supernovae have been proposed as the likely progenitor stars[1,7–11]. In all of these cases, the masses of the proposed progenitors are estimated to be in the range 8–20 $M_\odot$ (ref. 11), significantly below the implied mass of the luminous NGC266_LBV 1. Furthermore, with the exception of SN 1987A, only

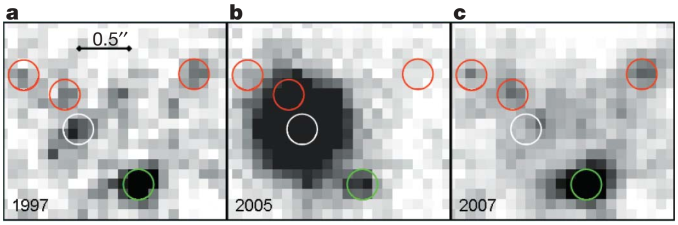

Figure 1 | The progenitor star of SN 2005gl vanished after the supernova event. a, A section from the reduced HST image of the galaxy NGC 266, taken on 1997 June 15.1 UT (8 years before the discovery[27] of SN 2005gl on 2005 October 5.18 UT), with the Wide Field and Planetary Camera 2 (WFPC2) using the F547M filter (in the green part of the visible light spectrum, centred at 547 nm), produced using Pydrizzle software (Supplementary Information section 1). North is up and east is due left. The luminous star NGC266_LBV 1 (white circle) is detected as a 6.2σ point source, with a flight magnitude of $V = 24.1 \pm 0.1$ mag, which translates to an absolute magnitude $m_V = -10.3$ (a luminosity of $1.1 \times 10^6 L_\odot$) at the distance[3] of NGC 266 (66 Mpc). Green and red circles are defined below. **b,** A high-resolution image of SN 2005gl obtained using the Near Infrared Camera 2 (NIRC2) behind the laser-guide-star-assisted adaptive optics system at the Keck II telescope in Mauna Kea, Hawaii, on 11 November 2005. The image of the supernova is registered to the pre-explosion HST image of the same area (**a**) using common point sources, to a precision of better than a fraction of a WF pixel[3]. SN 2005gl is precisely coincident with NGC266_LBV 1, with a formal offset of $0.02''$, well within the positional uncertainties of these objects. **c,** New HST imaging of this location obtained on 26 September 2007 UT, using the same instrument and filter as in 1997 (WFPC2/F547M) with a total exposure time of $4 \times 400 = 1{,}600$ s, reduced in a similar manner to the data from 1997 and registered onto the 1997 coordinate grid. Green circle shows a bright source near the supernova location easily visible in **a**–**c**; additional nearby sources (three examples marked in red circles) can be seen in both the new and old visible-light HST data (**a**, **c**) but not in the near-infrared (**b**). As can be seen by comparing **a**, **b** and **c**, SN 2005gl is no longer detected, and NGC266_LBV 1 has also vanished (compare with the nearby sources marked with red circles). These new data provide compelling evidence that the luminous star NGC266_LBV 1 indeed exploded as SN 2005gl in 2005.

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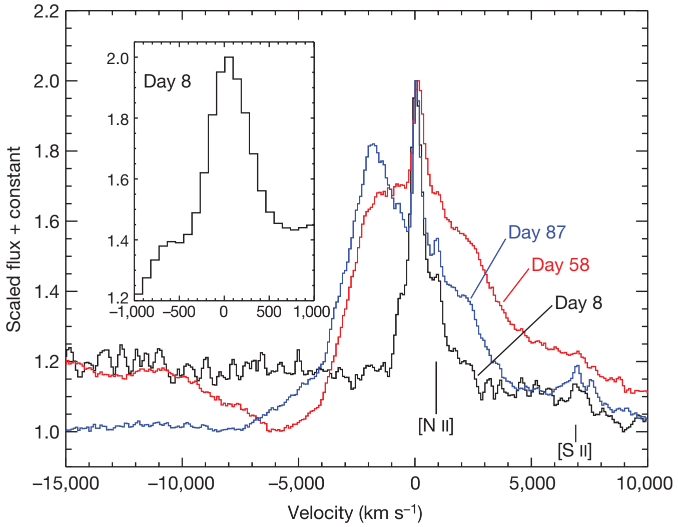

Figure 2 | Spectra of SN 2005gl centred on the region of the Hα emission line, presented in velocity scale. The velocity zero point is defined assuming $\lambda_0 = 6{,}562.85$ Å for this line and a systemic velocity $v = 4{,}661\ \mathrm{km\ s^{-1}}$ for NGC 266. Negative velocity values indicate blue-shifted emission coming from material moving towards the observer, while positive values indicate red-shifted emission from material moving away. The spectral resolutions are 3.4 Å for day 8, and 7 Å for days 58 and 87 (155 km s^{-1} and 320 km s^{-1} at Hα, respectively). The first-epoch spectrum (day 8; magnified view in inset) shows a narrow, resolved component of Hα, with $v \approx 420\ \mathrm{km\ s^{-1}}$, superposed on an intermediate-width component, with $v \approx 1{,}500\ \mathrm{km\ s^{-1}}$. (Note that velocities are determined from the half-width at zero-intensity (HWZI) of the line profiles, and have been corrected for the instrumental resolution of the spectrum at Hα ($\sim$155 km s^{-1}).) Narrow nebular lines of nitrogen and sulphur, most probably from unresolved H II region light, are also detected. The narrow component of Hα is probably also contaminated by unresolved H II region emission, but its width indicates a contribution from a mass shell ejected shortly before the supernova explosion. The velocity is typical of LBV eruptions, but is well in excess of typical red supergiant wind speeds (Supplementary Information section 5). The expansion velocity of the intermediate-width component probably corresponds to the velocity of the outgoing supernova blast wave ploughing through the slower pre-explosion mass loss, having been decelerated from an initial velocity that is typically ten times larger. No broad component is detected at this epoch, indicating that the photosphere effectively lies at the shock interaction zone, and shields the inner areas (including the fast, unshocked and freely expanding supernova ejecta and the supernova photosphere) from view. From the combination of the line widths and the intermediate-width line luminosity one can calculate the mass loss rate from NGC266_LBV 1 before its explosion, $\dot{M} \approx 0.03\, M_\odot\ \mathrm{yr^{-1}}$ (see main text). The derived mass-loss-rate value is corrected for Galactic extinction in the direction of SN 2005gl of $A_V = 0.23$ mag and an extinction range $A_V < 0.1$ mag in NGC 266. The second spectrum (day 58) has evolved dramatically. A broad component of the Hα emission line now dominates, with the intermediate-width component no longer evident. This indicates that the strong interaction phase is probably over, with the emission now dominated by fast, unshocked ejecta ($\sim$10,000 km s^{-1}, a typical speed for a supernova at this age) and the supernova photosphere. The spectrum now resembles that of non-interacting supernovae from lower-mass stars (type II-P events, Supplementary Information section 3; Supplementary Fig. 4). A narrow Hα emission remains visible, probably including contributions from both unrelated H II region light, as well as from photoionized unshocked wind surrounding the supernova; at the resolution of our last two spectra the line is only marginally resolved, so it is not possible to accurately determine a velocity for the material and thus discriminate between the two possibilities. The last spectrum (day 87) is nebular, with a wide, asymmetric Hα emission profile.

spatial coincidence supports the proposed progenitor identifications; that is, these objects could be, at least in principle, unrelated objects superposed near our line of sight to the supernova by chance[11–13].

The bright explosion of a supernova serves as a backlight that illuminates evidence for the last stages of the evolution of the progenitor star before explosion. We now demonstrate this for the case of SN 2005gl, following the recent[14] general description of the physics of a supernova blast wave expanding into a previously ejected mass shell (see also references within ref. 14). A detailed reanalysis of our spectroscopy of SN 2005gl[3] (Fig. 2; Supplementary Information) in this context reveals the following. Initially, the spectrum is dominated by a resolved narrow component (Fig. 2 inset) of the Balmer Hα emission line, superposed on an intermediate-width component. These probably arise from an unshocked outflowing shell of material ejected by the progenitor shortly before explosion, at a velocity of $\sim$420 km s^{-1} (narrow component), and the outgoing supernova blast wave ploughing through the slower pre-explosion mass loss at $\sim$1,500 km s^{-1} (intermediate component) acting as the effective photosphere. Our next spectrum, taken 50 days later, shows only a broad component of the Hα emission line, while the intermediate-width component is gone, indicating that the strong interaction phase is probably over, with the emission now dominated by fast, unshocked ejecta ($\sim$10,000 km s^{-1}). From nebular emission lines of nitrogen and oxygen near the supernova location, we can measure the amount of heavy elements in the gaseous environment of NGC266_LBV 1 (Supplementary Information section 4). Assuming that this is representative of the heavy element content of the short-lived progenitor star itself, we find that the progenitor of SN 2005gl was quite metal-rich, with an oxygen abundance that was $2.8^{+2.7}_{-1.4}$ times that of the Sun.

Assuming that the supernova blast wave went through the surrounding pre-explosion outflow at a velocity of $v_{\mathrm{shock}} \approx 1{,}500\ \mathrm{km\ s^{-1}}$ and essentially had emerged from it by day 58, and given the outflow velocity was $v_{\mathrm{wind}} \approx 420\ \mathrm{km\ s^{-1}}$, the final mass loss episode must have begun no more than about half a year before the final explosion of the star. We use these velocities, and the luminosity of the intermediate-width component of the Hα emission line ($L_{\mathrm{int}} = 2.8 \times 10^{39}\ \mathrm{erg\ s^{-1}\ cm^{-2}}$; Supplementary Information section 5)—which presumably arises from the shocked gas layer—to derive the mass loss rate $\dot{M}$ during the final, pre-supernova outburst of the progenitor star through the formula[15] $L_{\mathrm{int}} = \epsilon_{H\alpha} \dot{M} v_{\mathrm{shock}}^3 / 4 v_{\mathrm{wind}}$. Adopting an efficiency factor $\epsilon_{H\alpha} = 0.1$, appropriate for young supernovae[15], we find a value of $\dot{M} \approx 0.03\, M_\odot\ \mathrm{yr^{-1}}$, which is similar, for example, to that of the LBV P Cygni during its giant eruptions. As the final mass-loss episode lasted for less than a year, our data suggest that the total amount of mass lost just before explosion was modest, and was overrun by the supernova ejecta early on (compare ref. 14), which is in accord with the unremarkable luminosity and moderately rapid decline of the light curve of this supernova[3].

The fact that a very luminous and hence very massive star exploded during an LBV-like phase requires a modification in theoretical evolutionary models of extremely massive stars, which generally predict that massive stars should explode after the LBV phase has ended[16,17]. Furthermore, such models predict that high metallicity stars, similar to that of NGC266_LBV 1, should lose their hydrogen-rich outer envelopes and evolve into stripped hydrogen-poor stars, and end their lives in hydrogen-free supernova explosions some 10^5 years later. Evidently, this was not the fate of NGC266_LBV 1. Our observations thus bolster previous suggestions[3,18–20] that at least some massive hypergiant stars explode during, or shortly after, a violent LBV-like eruption phase, as hydrogen-rich supernovae in which the ejecta interact almost immediately with the slowly moving shells from prior eruptions.

The lack of an extended plateau in the optical light curve of SN 2005gl[3] indicates that the progenitor star did not retain a substantial hydrogen envelope, as models suggest that as little as $10 M_\odot$ are enough to support a plateau phase[21]. We have shown that NGC266_LBV 1 lost only a modest amount of mass ($<0.1 M_\odot$) in the eruption episode immediately before its final explosion. Therefore, although NGC266_LBV 1 was initially composed mostly of hydrogen, it must have lost many tens of solar masses of hydrogen in previous mass ejection episodes, which may have manifested as a variety of luminous supernova-like events that did not destroy the star[22,23] (Fig. 3). In any case, our observations strongly constrain the mass loss properties of a very massive star before explosion, which

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relevant models must recover. According to standard models[24], the likely remnant of the explosion of such a massive star, suffering only limited mass loss (as it retained enough hydrogen to make a type II supernova), is a stellar-mass black hole.

Based on the solid foundation laid by the unambiguous association of the type IIn supernova SN 2005gl with a very luminous hypergiant progenitor undergoing LBV-like mass loss, a synthesis of the entire range of related phenomena (for example, LBV eruptions, supernova precursors[25] and impostors[26], putative shell-shell supernova-like events[23] and the final explosions; Fig. 3) can be used to map out the violent lives and deaths of the most massive stars.

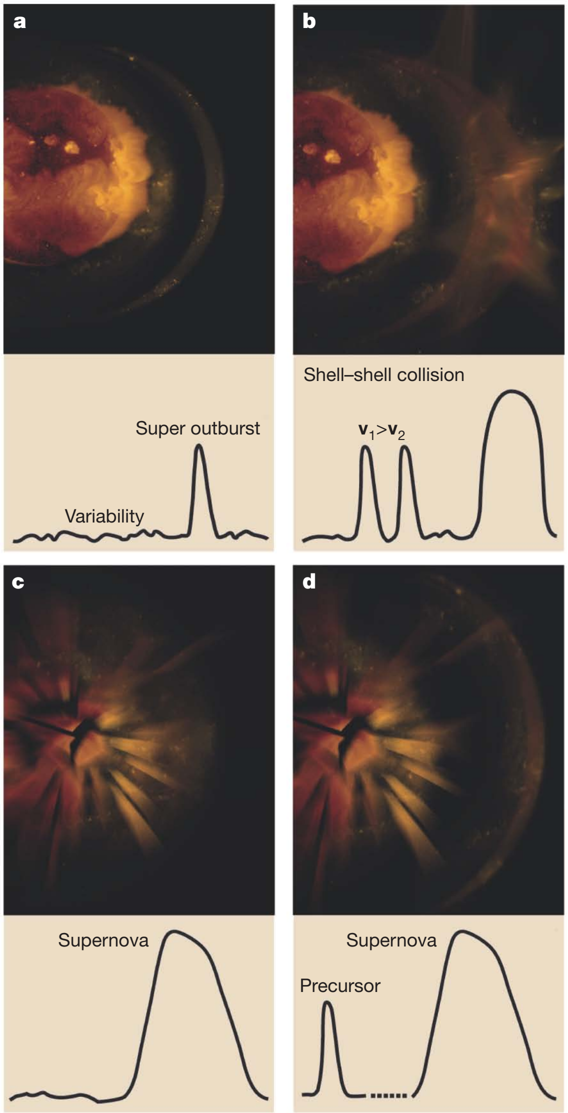

Figure 3 | Graphic illustrations of various manifestations of the violent evolution of the most luminous stars. a, LBVs suffer frequent eruptions (with a typical mass-loss rate of around $10^{-2} M_\odot \mathrm{yr}^{-1}$) accompanied by relatively low-level (of the order of 50%) variability[4] (line graphs at the bottom of panels illustrate temporal flux evolution, with time flowing due right). Less frequent 'super outbursts' may involve the ejection of massive, many-solar-mass shells[4,28], along with very luminous optical displays, during which the luminosity of the star may increase by an order of magnitude or more. These events (sometimes called supernova impostors[26]) can therefore be confused with genuine supernova explosions. **b,** Collisions between a faster massive ejected shell ($\mathbf{v}_1$) and a slower one ($\mathbf{v}_2$) have been speculated to result in very luminous events, comparable energetically to bright supernova explosions, but which do not lead to a total destruction of the star[22,23]. **c,** Our observations show that such luminous stars can evolve and explode as supernovae, after having previously lost some, but not all, of their hydrogen envelopes. The interaction of the expanding debris from the supernova explosion with previously lost mass will result in strong shocks, producing the typical signatures of type IIn supernovae. **d,** Super outbursts occurring shortly before the final explosion of such stars can appear as supernova precursors[25].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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