LETTERS

A faint type of supernova from a white dwarf with a helium-rich companion

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Supernovae are thought to arise from two different physical processes. The cores of massive, short-lived stars undergo gravitational core collapse and typically eject a few solar masses during their explosion. These are thought to appear as type Ib/c and type II supernovae, and are associated with young stellar populations. In contrast, the thermonuclear detonation of a carbon-oxygen white dwarf, whose mass approaches the Chandrasekhar limit, is thought to produce type Ia supernovae[1,2]. Such supernovae are observed in both young and old stellar environments. Here we report a faint type Ib supernova, SN 2005E, in the halo of the nearby isolated galaxy, NGC 1032. The 'old' environment near the supernova location, and the very low derived ejected mass (~0.3 solar masses), argue strongly against a core-collapse origin. Spectroscopic observations and analysis reveal high ejecta velocities, dominated by helium-burning products, probably excluding this as a subluminous[3,4] or a regular[1] type Ia supernova. We conclude that it arises from a low-mass, old progenitor, likely to have been a helium-accreting white dwarf in a binary. The ejecta contain more calcium than observed in other types of supernovae and probably large amounts of radioactive ^{44}Ti.

We discovered a supernova explosion (SN 2005E; Fig. 1) on 2005 January 13 (UT dates are used throughout this paper) shortly after it occurred (it was not detected on 2004 December 24). Follow-up spectroscopy (Fig. 2) revealed strong lines of helium and calcium, indicating that it belongs to the previously identified group of calcium-rich type Ib supernovae[5]. The supernova position is ~22.9 kpc (projected) from the centre, and ~11.3 kpc above the disk, of its edge-on host galaxy, NGC 1032 (Fig. 1), which is itself at a distance of 34 Mpc. NGC 1032 is an isolated galaxy[6] showing no signs of interaction, with the closest small satellite galaxy found at a distance >120 kpc in projection. Deep follow-up observations of the explosion site, sensitive to both ultraviolet light from hot young stars and emission lines from ionized hydrogen gas, put strict limits on any local star-formation activity at or near the supernova location (Fig. 1). In addition, a radio signature, expected from some core-collapse supernovae, has not been observed (Supplementary Information section 2).

Our analysis of the spectra of SN 2005E indicates that it is similar to type Ib supernovae (Fig. 2 and Supplementary Information section 3), showing lines of He but lacking either hydrogen or the hallmark Si and S lines of type Ia supernovae in its photospheric spectra. The nebular spectrum of this event shows no emission from iron-group elements, which also characterize type Ia supernovae (Supplementary Information sections 3 and 4). Analysis of this spectrum indicates a total ejected mass of $M_{ej} \approx 0.275 M_\odot$ ($M_\odot$, solar mass), with a small fraction in radioactive nickel, consistent with the low luminosity of this event. Such low ejecta mass for a supernova of any type has not previously been firmly established using nebular spectral analysis (Supplementary Fig. 3 and Supplementary Information section 5). We also used the narrow, fast and faint light curve (Supplementary Information, Supplementary Fig. 4) together with the measured ejecta velocity (~11,000 km s^{-1}) to infer the ejected mass (Supplementary Information section 6). We use these data to find consistent results of $M_{ej} \approx 0.3 \pm 0.1 M_\odot$, assuming that some of the mass is not accounted for by the nebular spectrum analysis (for example, high-velocity He layers and some slowly moving, denser ejecta that are still hidden below the photosphere at that time). Finally, SN 2005E exhibits a remarkable amount of calcium in its ejecta, $0.135 M_\odot$ (~0.49 of the total ejecta mass), 5–10 times more than typical supernovae of any variety, with a relative calcium fraction 25–350 times higher than any reported values for other supernovae (Supplementary Table 1 and Supplementary Information section 7), while not showing evidence for sulphur (Supplementary Information section 4).

The remote position of SN 2005E in the outskirts (halo) of the galaxy, together with the isolation of NGC 1032 and its classification as an S0/a galaxy (in which the star-formation rate is very low[7]), in addition to our limits on local star formation, point to a supernova progenitor from an old stellar population (see also Supplementary Information section 2). In addition, the low ejected mass and nucleosynthetic output of SN 2005E are in stark contrast to those expected from collapsing massive stars, whether formed locally or ejected from a distant location (Supplementary Information sections 8 and 9).

The low ejected mass is also inconsistent with those determined for type Ia supernovae, restricted to a tight mass range of ~1–1.3$M_\odot$, regardless of their intrinsic luminosity (even the prototype faint SN

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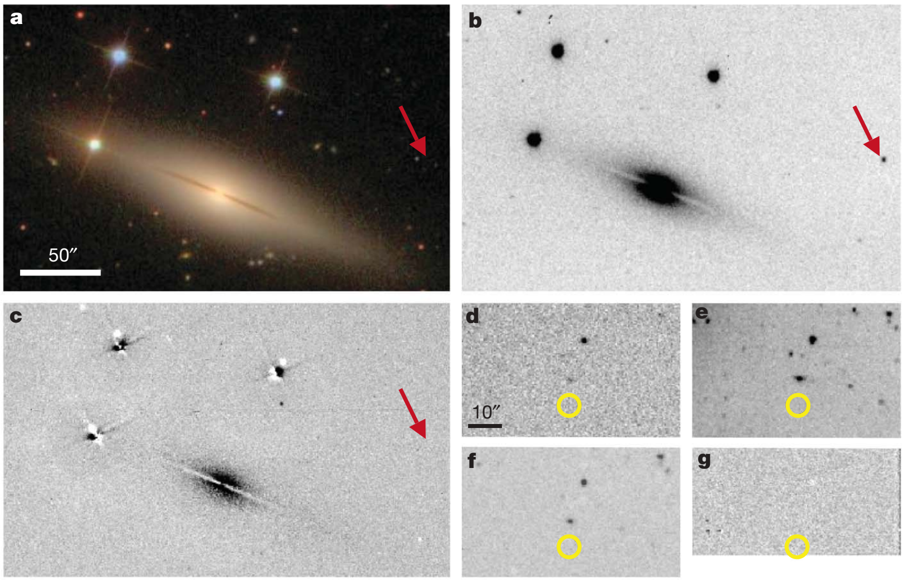

Figure 1 | The environment of SN 2005E. **a**, NGC 1032, the host galaxy of SN 2005E, as observed by the Sloan Digital Sky Survey (SDSS), before the supernova explosion. The galaxy is an isolated, edge-on, early-type spiral galaxy, showing no signs of star-formation activity, warping or interaction. Its luminosity is dominated by the cumulative contribution of a multitude of low-mass old stars (yellow light in this image). **b**, The LOSS[29] discovery of SN 2005E on 2005 January 13 (shown in negative). Note the remote location of the supernova (marked with a red arrow) with respect to its host, 22.9 kpc (projected) from the galaxy nucleus and 11.3 kpc above the disk, whose edge-on orientation is well determined (**a**). **c**, An image of NGC 1032 in the light of the Hα emission line, emitted by interstellar gas ionized by ultraviolet radiation, and a good tracer of recent star formation. There are no traces of recent star-formation activity (usually appearing as irregular, compact emission sources) near the supernova location or anywhere else in the host. Panels **a**–**c** are 275″ × 175″; north is up, and east is to the left; scale bar in **a** applies to **b** and **c** also. **d**, Zoom-in on the location of SN 2005E in pre-explosion SDSS r-band images. No source is detected near the supernova location, marked with a yellow circle (radius 3″; the astrometric uncertainty in the supernova location is <0.5″). The SDSS catalogue does not list any objects near that position (for example, putative faint dwarf satellites of NGC 1032), down to a typical limit of $r = 22.5$ mag. **e**, **f**, Deeper photometry of the supernova location. A red image is shown in **e**, while an ultraviolet (u-band) image is shown in **f**. At the distance of NGC 1032, the point-source upper limits we find, $M_r < -7.5(-6.9)$ and $M_{u'} < -8.1(-7.1)$ mag at $3(2)\sigma$, respectively, indicate that we would have detected faint star-forming galaxies or star-forming regions at the supernova location, or indeed even individual massive red supergiant or luminous blue supergiant stars. **g**, Zoom-in on the location of SN 2005E in Hα light (see **c** for details). No trace of star-formation activity is seen near the supernova location. Panels **d**–**g** are 64″ × 36″; scale bar in **d** applies also to **e**–**g**. Technical details about the observations can be found in Supplementary Information section 1.

1991bg is found in this range)[2]. Furthermore, the light curve of SN 2005E (Supplementary Information section 6) shows a different behaviour from that of type Ia supernovae, declining much faster than even the most subluminous (SN 1991bg-like) events observed[8]. These properties, together with the observed He-rich spectra and inferred composition, rule out SN 2005E as being either a regular or peculiar type Ia supernova (see also discussion in Supplementary Information section 10, regarding the very subluminous SN 2008ha and other related peculiar supernovae[4,9,10]). Therefore, we conclude that SN 2005E is the first clearly identified example of a new, different type of supernova explosion, arising from a He-rich, low-mass progenitor.

The spectroscopic signatures of SN 2005E are quite unusual, and allow one to identify additional similar events[5]. Arising from lower-mass progenitors, these events are likely to be found among both old and young stellar populations—that is, we expect to find such peculiar type Ib supernovae in both early- and late-type galaxies. Indeed, while the unusual location of SN 2005E triggered the current study, several other calcium-rich subluminous type Ib/c supernovae similar to SN 2005E have been observed (Supplementary Information section 11). Of the group of eight subluminous calcium-rich type Ib/c supernovae identified (seven identified by us and an additional one described in ref. 11), four are observed in old-population environments: SN 2005E presented here, as well as SN 2000ds, SN 2005cz and SN 2007ke, residing in elliptical galaxies. SN 2000ds has pre- and post-explosion Hubble Space Telescope images showing no evidence for either star-forming regions or massive stars[12] near its location. The host-galaxy distribution of the supernovae in our sample (Fig. 3) is inconsistent with that of any core-collapse supernova. Neither have radio signatures been observed (Supplementary Information section 11). Thus, all evidence suggests that a well-defined subset of type Ib supernovae, all having Ca-rich spectra and faint peak magnitudes, comprise a distinct physical class of explosions coming from low-mass, old progenitors. This class includes all known type Ib/c events in confirmed elliptical galaxies[13,14] (Supplementary Information section 11). A different interpretation[11], invoking the core collapse of a massive progenitor, was suggested for one of these events (SN 2005cz). It is difficult to reconcile our observations and analysis of SN 2005E with such an interpretation, which is also inconsistent with the host-galaxy distribution of all of the other Ca-rich type Ib supernovae in our sample.

Calcium-rich supernovae were theoretically predicted to arise from burning helium-rich material on a white dwarf (for example, a helium white dwarf or a helium star accreting onto a carbon-oxygen white dwarf), leading to the full disruption of a sub-Chandrasekhar-mass white dwarf[15,16]. However, such models predicted the production of supernovae far more luminous (and ^{56}Fe rich) than SN 2005E. Several theoretical models were suggested in the literature to possibly produce subluminous supernovae, with low-mass and high-velocity ejecta in an old stellar population. These include the accretion-induced collapse of a white dwarf (see, for example, refs 17 and 18), and the detonation of an accreted helium shell on a white dwarf in a binary system (the '.Ia' model[19]). These studies did not explore the burning of large helium masses ($>0.1M_\odot$), nor the production of calcium-rich ejecta. Multi-dimensional simulations of a detonation in accreted He layers[20] showed (for low-mass white dwarfs; $M = 0.7M_\odot$) a trend towards large Ca abundances and high Ca/S abundance ratios (a high ratio is inferred for SN 2005E; Supplementary Information section 4) and a light curve that was faster and dimmer than those of typical type Ia supernovae (but still much more luminous than SN 2005E), as well as a high production of ^{44}Ti. It is possible that similar models, with less

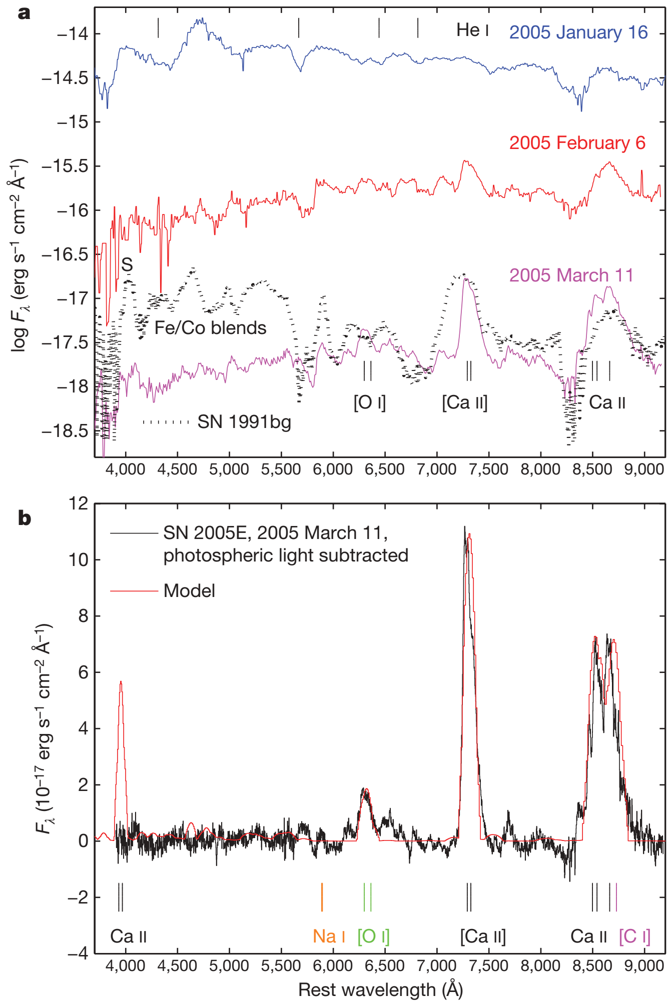

Figure 2 | The mass and composition of the ejecta of SN 2005E. **a**, Photospheric spectra of SN 2005E. The top spectrum is obviously photospheric and shows absorption lines of the He I series (marked with black ticks after application of an 11,000 km s^{-1} blueshift, at the top). Nebular lines of intermediate-mass elements, most notably calcium, begin to emerge in the middle spectrum. Calcium dominates the latest nebular spectrum at the bottom, and nebular oxygen is visible as well. We note that the typical Si lines of type Ia supernovae are absent in all spectra, while the nebular spectrum of SN 2005E clearly rules out a type Ia identification (comparison with the underluminous SN 1991bg is shown; note the lack of the typical iron-group line blends in the blue side). The derived line velocities are consistent with SN 2005E exploding within its putative host galaxy, NGC 1032. **b**, The nebular spectrum of SN 2005E compared with a model fit. From the fit we can derive elemental abundances and masses in the ejecta of SN 2005E. We find masses of 0.1, 0.037, 0.135 and 0.003$M_\odot$ for carbon, oxygen, calcium and radioactive nickel, respectively. Both the low total ejected mass of $\sim$0.275$M_\odot$ and the relative abundances are unique among previously studied events. The lack of prominent C/O-burning products such as S and Fe (typically seen in type Ia supernovae; Supplementary Information section 4) argues against a C/O white dwarf origin. Technical details of observations and additional references can be found in Supplementary Information section 1.

burning of C and O to make S and Ni, may resemble SN 2005E. This gains additional support from our nucleosynthetic analysis (Supplementary Information section 12), showing that the unique composition of SN 2005E could be produced, in principle, as the product of He ignition. Further studies in these directions are in progress.

We conclude that SN 2005E appears to be the first observed manifestation of the helium detonation process. This event most probably occurred in an interacting double white-dwarf system with a helium white-dwarf mass donor. Additional characteristics of these explosions, including their old population origin, He-rich spectra, subluminosity

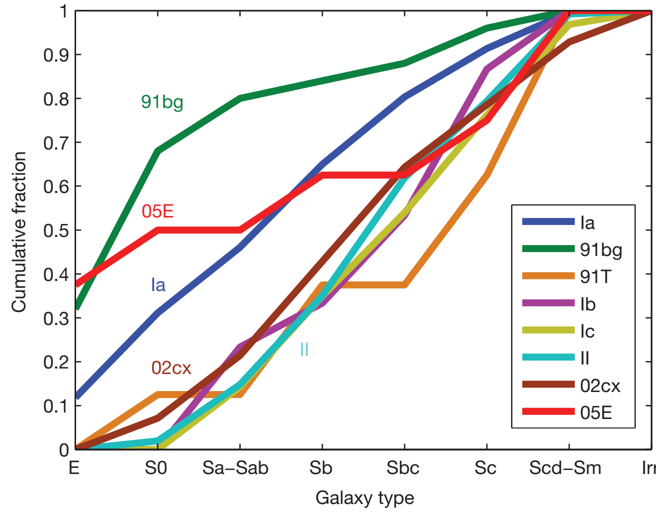

Figure 3 | The cumulative distribution of host galaxies of supernovae from the KAIT (Katzman Automatic Imaging Telescope) supernova survey. We corrected the classification of a few hosts of type Ib/c supernovae using higher-quality observations from the Palomar 60-inch telescope (SN 2005ar, SN 2006ab and SN 2006lc were found to be hosted by spiral galaxies rather than elliptical galaxies). After correcting the classification, we find that all type Ib/c supernovae found in early-type galaxies are faint Ca-rich supernovae similar to SN 2005E. Note that the SN 2005E-like supernova host distribution is very different from that of other type Ib/c supernovae, as well as that of type II (known to have young massive progenitors) and that of SN 2002cx-like type Ia, with half of the SN 2005E-like group (four out of eight) observed in early-type (elliptical or S0) galaxies. The progenitors of SN 2005E and the other members of its group are therefore likely to belong to an old, low-mass stellar population. The total numbers of host galaxies included in this figure are 244, 25, 8, 257, 30, 63, 14, and 8 for supernovae of types Ia, SN 1991bg (91bg), SN 1991T (91T), II, Ib, Ic, SN 2002cx (02cx) and SN 2005E (05E), respectively.

and low ejected mass, are broadly consistent with the predictions of some theoretical models (.Ia[19]; accretion-induced collapse[18]; helium detonation[21]), variants of which may produce the appropriate conditions for such helium detonations. Alternatively, these explosions may require a new mechanism.

Our discovery has numerous astrophysical implications. It seems highly likely that we identified explosions arising from very close white dwarf/white dwarf systems, the rates of which (Supplementary Information section 11) might be useful for predicting the rates of white dwarf/white dwarf inspirals observable as gravitational wave sources. The unique nucleosynthetic production of large masses of calcium and radioactive ^{44}Ti per explosion could solve puzzles related to the source of calcium (especially ^{44}Ca) in the primitive Solar System[22,23] and in old, metal-poor halo stars[24], and the enrichment patterns of the interstellar and intracluster medium[25]. Production of most of the Galactic ^{44}Ti and its progeny, ^{44}Ca, in a few rare, prolific explosions, can also explain the origins of Galactic ^{44}Ca, given the null detection of ^{44}Ti traces in most nearby supernova remnants[23,26].

Finally, inverse β decay of ^{44}Ti may significantly contribute to the Galactic production of positrons[27]. Assuming our estimated rates ($\sim$10% of the type Ia supernova rate; Supplementary Information section 11) and our ^{44}Ti yield (0.014–0.14$M_\odot$; Supplementary Information section 12), Galactic supernovae of the type we describe here will provide a significant contribution to the Galactic bulge component of the positron annihilation 511 keV γ-ray line, at least comparable to that of type Ia supernovae. In fact, within the current uncertainties on the ^{44}Ti yield and supernova rates, these events may come within a factor of a few of producing all of the observed positrons[28].

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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 H.B.P. led the project, performed the calculations related to hyper-velocity stars, examined other putative SN 2005E-like events, collected and analysed archival data concerning supernova properties and their hosts, and wrote the manuscript. A.G.-Y. is the Principal Investigator of the CCCP programme and initiated the project, collected and analysed photometric and spectroscopic data, coordinated further observational and theoretical work, and managed the project. P.A.M. conducted the nebular spectral analysis and its interpretation, and determined the elemental abundances in the ejecta. D.A. determined that the measured composition requires He burning and performed nucleosynthesis calculations to confirm this. D.K. investigated local star-formation tracers at the location of SN 2005E. A.V.F. and W.L. contributed spectroscopic and photometric observations and reductions of SN 2005E and of similar Ca-rich objects, a class they originally identified, and provided most of the data on supernova host galaxies. A.V.F. also edited the paper. I.A. analysed the CCCP photometry of SN 2005E and cross-calibrated it with other data. S.B.C., D.B.F., D.C.L., D.-S.M., D.J.S. and A.M.S. are members of the CCCP and contributed to initial observations of SN 2005E. J.P.A. and P.A.J. obtained and analysed narrow-band images of NGC 1032 and the location of SN 2005E. R.J.F. and M.G. contributed to spectroscopic observations and reductions. E.O.O. obtained deep photometric observations of the location of SN 2005E. L.B., G.N., K.J.S. and N.N.W. investigated the relation of SN 2005E to .Ia models and contributed to the text. B.D.M., A.L.P. and E.Q. investigated the relation of SN 2005E to accretion-induced collapse models and contributed to the text. M.K. performed custom reductions of CCCP spectra. D.P. carried out synthetic photometry analysis.

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