

## LETTERS

# Discovery of the progenitor of the type Ia supernova 2007on

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Type Ia supernovae are exploding stars that are used to measure the accelerated expansion of the Universe<sup>1,2</sup> and are responsible for most of the iron ever produced<sup>3</sup>. Although there is general agreement that the exploding star is a white dwarf in a binary system, the exact configuration and trigger of the explosion is unclear<sup>4</sup>, which could hamper their use for precision cosmology. Two families of progenitor models have been proposed. In the first, a white dwarf accretes material from a companion until it exceeds the Chandrasekhar mass, collapses and explodes<sup>5,6</sup>. Alternatively, two white dwarfs merge, again causing catastrophic collapse and an explosion<sup>7,8</sup>. It has hitherto been impossible to determine if either model is correct. Here we report the discovery of an object in pre-supernova archival X-ray images at the position of the recent type Ia supernova (2007on) in the elliptical galaxy NGC 1404. Deep optical images (also archival) show no sign of this object. From this we conclude that the X-ray source is the progenitor of the supernova, which favours the accretion model for this supernova, although the host galaxy is older (6–9 Gyr) than the age at which the explosions are predicted in the accreting models.

The two proposed progenitor models of type Ia supernovae are radically different. In the accreting model a prolonged phase of mass transfer precedes the explosion, often identified with the bright so-called supersoft X-ray sources, binary stars in which the mass transfer is believed to be just fast enough to sustain steady nuclear burning on the surface of the white dwarf<sup>9</sup>. In the merger model the mass growth is extremely rapid during the merger, but there is no mass transfer before the explosion, and it is expected that such progenitors will be extremely faint. However, it has been suggested that the mass growth might be slowed down significantly by the rapid rotation of the system<sup>10</sup>, easing the problems with the triggering of the explosions when the mass growth is too rapid<sup>11</sup>. In that case there would be thousands of years between the merger and the actual explosion, and the progenitors might also be X-ray sources.

Attempts to distinguish between the models have been based on indirect methods. Calculations of the rate at which supernovae occur as a function of the age of the stellar population show that the mergers occur in populations of all ages whereas the accreting models tend to occur mostly at intermediate ages (~200 Myr to ~2 Gyr)<sup>12,13</sup>, and from the statistics of observed supernovae there is a growing evidence for a two-component model for the rates (one component proportional to star formation and one proportional to mass)<sup>14,15</sup>. Other attempts to constrain the progenitors have come from very detailed studies of the spectra of the supernovae<sup>16,17</sup>, and attempts have been made to search for the companion stars in supernova remnants<sup>18</sup>. We have taken a different approach by searching for ways to directly detect the progenitor of a type Ia supernova in pre-supernova images of the position in the sky where the supernova occurred.

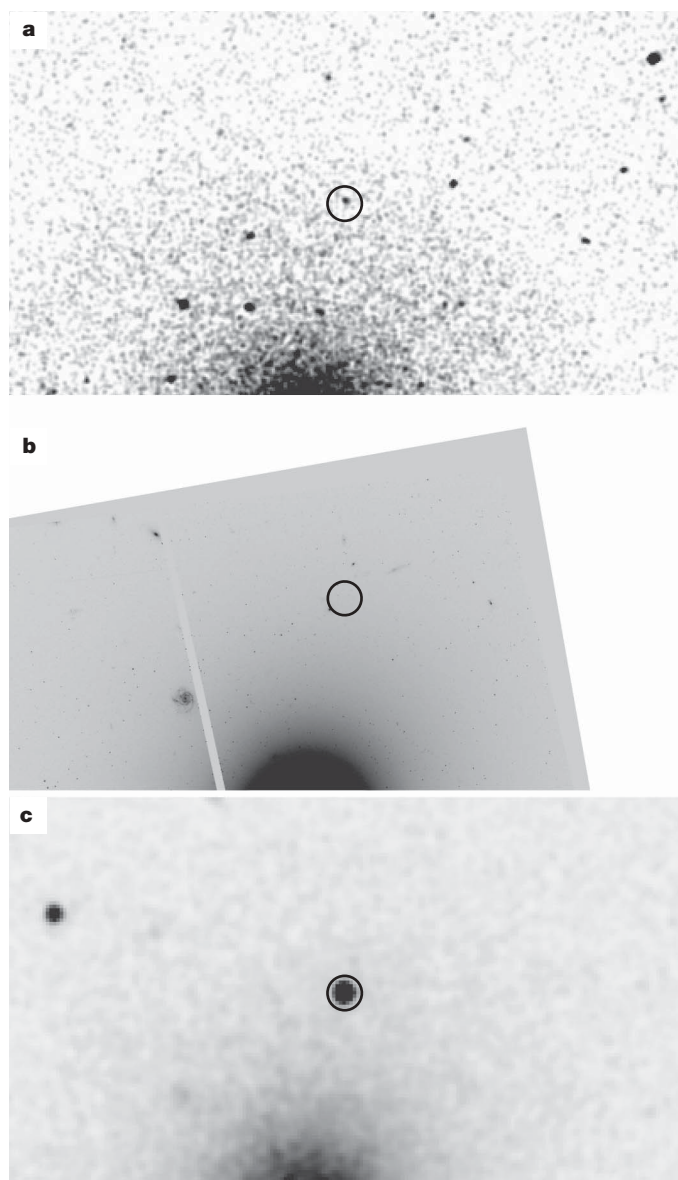
On 2007 November 5, supernova SN2007on was found in the outskirts of the elliptical galaxy NGC 1404<sup>19</sup>. Optical spectra of the supernova<sup>20</sup> showed that the supernova was of type Ia. The position of the supernova, at RA = 03 h 38 m 50.9 s, dec. =  $-35^{\circ} 34' 30''$  (J2000), is about 70'' from the core of the host, corresponding to 8 kpc for a distance of 20 Mpc to NGC 1404<sup>21</sup>. Observations by the SWIFT mission on November 11 detected the supernova in the optical/ultraviolet monitor but not in the X-ray telescope<sup>22</sup>. We analysed the SWIFT data and determined the position of the supernova as RA = 03 h 38 m 50.98 s, dec. =  $-35^{\circ} 34' 31.0''$  (J2000), with uncertainty of 1'' (Fig. 1). The highest magnitude is  $V \approx 13$  (on November 16), yielding an absolute magnitude of  $M_v \approx -18.5$  and making it a rather faint type Ia supernova<sup>23</sup>. NGC 1404 is an elliptical galaxy in the Fornax cluster and its colours suggest that its stellar population is old, with estimates ranging from 6 to 9 Gyr (error about 2 Gyr) and no sign of recent star formation<sup>24,25</sup>.

We investigated the supernova position, using archival data before the explosion from the Hubble Space Telescope and Chandra X-ray Observatory, to search for a possible progenitor to the type Ia supernova (Fig. 1). In the Chandra observations obtained in 2003 a source is detected close to the position of the supernova, at the coordinates RA = 03 h 38 m 50.91 s, dec. =  $-35^{\circ} 34' 30.9''$  (with a  $1\sigma$  statistical error of 0.25'', as well as a  $\sim 0.5''$  error on the absolute astrometric precision, based on correlations between X-ray sources and the images of the region taken by the Two Micron All Sky Survey, 2MASS, and Digitized Sky Survey, DSS). No optical source was detected to an absolute magnitude limit of  $-4.5$ . The X-ray source is  $0.9 \pm 1.3''$  (mean  $\pm$  s.d.) from the supernova, consistent with being its progenitor. The X-ray source is detected with  $14.1 \pm 4.6$  counts, a  $4.0\sigma$  significance using circular aperture photometry, and  $5.0\sigma$  based on a wavelet analysis using the program wavdetect. Within a radius of 1' from the supernova position there are seven detected sources, giving a density of detected sources of  $2.2 \pm 0.8$  per square arcminute. The probability of a chance coincidence of a source within a distance of 1.3'' of the supernova position is therefore 0.3%. Even given the fact that this is not the first trial but the fourth (see below), the likelihood of a chance alignment is very small. As globular clusters are known to be abundant in low-mass X-ray binaries, the alignment of an X-ray source and the supernova would not be so significant if the supernova went off in a globular cluster. But this possibility is excluded by the non-detection of a source in the optical images. We therefore conclude that we have detected the progenitor of 2007on.

With the low number of counts it is impossible to determine the shape of the X-ray spectrum of the progenitor. Instead we investigate the source properties using the number counts in the source and background regions in three different energy bands, S (0.3–1.0 keV), M (1.0–2.0 keV) and H (2.0–8.0 keV). The results are  $S = 12$ ,  $M = 4$ ,  $H = 5$ , with background expectations of  $3.8 \pm 2.1$ ,

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**Figure 1 | Images of the region around SN2007on.** The images were taken by the Chandra X-ray observatory (**a**, archival pre-supernova image), Hubble Space Telescope (**b**, archival pre-supernova image) and SWIFT (**c**, optical image of supernova), and are smoothed by a Gaussian with a two-pixel FWHM. The circle gives a 5'' radius around the position of the supernova (the circle is much larger than the positional uncertainty). The central parts of NGC 1404 are visible south of the supernova position. There are eight archival Chandra imaging observations with the supernova position within the field of view. Only two of these (Observation ID numbers 2942 and 4174 taken on 2003 February 13 and 2003 May 28, with a combined exposure time of 74.9 ks) have telescope pointings within 6' of the supernova position and thus enough sensitivity to be useful. We added the two observations, and the resulting image is shown in **a**. Within an aperture of 2'' the X-ray source has 21 counts, whereas a background region in the annulus 2–10'' has 165 counts giving an expectation value of 6.9 counts in the source region. The Poisson probability of having 21 or more counts with this background level is  $1.12 \times 10^{-5}$ , so the source is detected with a significance of 4.0 and the number of source counts is  $14.1 (\pm 4.6)$ . In the Hubble Space Telescope archive there are four images from the Wide Field and Planetary Camera (WFPC2), four from the Advanced Camera for Surveys (ACS) and one from the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) that cover the position of the supernova. No source is present within 2'' of the given position in any of the images. The deepest (ACS) images in the F475W band (760 s, taken 2004 September 10) and F814W band (1.224 ks, taken 2006 August 6) have a limiting magnitude of about 27, corresponding to an absolute magnitude of  $-4.5$ . The image with the F475 filter is shown in **b**. In **c** we show a V-band image taken by the SWIFT ultraviolet/optical telescope (2007 November 11).

$2.0 \pm 1.4$  and  $1.1 \pm 1.2$ , respectively. Analysis of all (eight) individual images available in the Chandra archive shows no sign of variability. The luminosity of the source for a distance of 20 Mpc is  $(3.3 \pm 1.5) \times 10^{37} \text{ erg s}^{-1}$  (for a flat photon spectrum in each band, a power law with index 2 gives  $(2.2 \pm 0.9) \times 10^{37} \text{ erg s}^{-1}$ ).

In the archives there are three more type Ia supernovae in galaxies with a distance of less than 25 Mpc (all lenticular galaxies) and with Chandra observations longer than 10 ks before the supernova explosion. We do not detect an X-ray source at the position of the supernova in any of them. The  $3\sigma$  upper limits, obtained using the same aperture method as above and assuming the same spectral model, are presented in Table 1, together with the parameters of 2007on.

The discovery of a luminous X-ray source that is likely to be the direct progenitor of 2007on has important consequences for our understanding of type Ia supernovae. The X-ray luminosity is fully consistent with the typical luminosities of supersoft sources<sup>26</sup>, which are similar to the expectations from the accreting progenitor model. Also, their absolute magnitudes<sup>26</sup> are around  $-1$  to  $-2$ , consistent with the non-detection in the optical images. If in the merger model the explosion immediately follows the actual merger, the progenitor is not expected to emit X-rays before the supernova explosion, and this is therefore inconsistent with the observed progenitor of SN2007on. However, if the lower-mass white dwarf is disrupted at the onset of Roche-lobe overflow and forms a long-lived disk around the more massive white dwarf<sup>10</sup>, the merged object may be a strong X-ray source before the explosion. Recent detailed calculations of these objects suggest that they would have X-ray luminosities about an order of magnitude lower than the progenitor that we have discovered<sup>27</sup>. We therefore conclude that our result favours the accreting model. Alternatively, very high accretion rates in the early phases of the evolution of AM CVn systems can also lead to steady burning on white dwarfs, but now of accreted helium<sup>28</sup>. Although the rate of type Ia supernovae from this channel is very low, it is consistent with the properties of the progenitor.

The spectrum of the progenitor is relatively hard, compared with typical supersoft sources which have temperatures below 100 eV. A 100-eV black-body model can be ruled out, but models with 200–300 eV and a modest intrinsic absorption of  $10^{21} \text{ atoms cm}^{-2}$  are consistent with the observed counts. In addition the age of the stellar population of NGC 1404 could pose a problem for the supersoft source interpretation: the models predict lifetimes only up to about 2 Gyr (refs 11, 12), considerably younger than the inferred age of the population of NGC 1404. This may indicate that the progenitor was a lower-mass

**Table 1 | Nearby type Ia supernovae observed with Chandra before the explosion**

Supernova	2007on	2006mr	2004W	2002cv
Galaxy	NGC 1404	NGC 1316	NGC 4649	NGC 3190
Galaxy type	Elliptical	Lenticular (Sa)	Lenticular (S0)	Lenticular (Sa)
Distance (Mpc)	20	18.1	15.9	22.4
Observation ID	2942 and 4174	2022	785	2760
Time before supernova	~4 yr	~5 months	~4 yr	~2 months
Count rate ( $\text{s}^{-1}$ )	$(1.9 \pm 0.6) \times 10^{-4}$	$<9.2 \times 10^{-4}$	$<3.2 \times 10^{-4}$	$<3.6 \times 10^{-4}$
Luminosity ( $\text{erg s}^{-1}$ )	$(3.3 \pm 1.5) \times 10^{37}$	$<1.3 \times 10^{38}$	$<3.5 \times 10^{37}$	$<7.9 \times 10^{37}$

system, such as a symbiotic binary, for which hard X-rays have recently been discovered<sup>29</sup>. However, it cannot be excluded that a small population of younger stars is present in the host galaxy of 2007on.

Our discovery opens a new method for the study of type Ia supernova progenitors. This first detection favours the accreting model and the three upper limits on previous supernovae are not strong enough to provide additional constraints. But this does not prove that the other models cannot lead to type Ia supernovae. Searches for supersoft sources in nearby galaxies have resulted in many fewer supersoft sources than expected and needed to explain all type Ia supernovae (see online results at ([http://online.itp.ucsb.edu/online/snovae\\_c07/distefano/](http://online.itp.ucsb.edu/online/snovae_c07/distefano/))), even though the strong variability of these sources complicates the analysis. Also, the growing support for a two-component model for the rate of supernovae may well indicate that the two progenitor models are complementary. Future detections or strong upper limits on pre-supernova X-ray luminosities are important for the understanding of this issue.

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1. Riess, A. G. *et al.* Observational evidence from supernovae for an accelerating universe and a cosmological constant. *Astron. J.* **116**, 1009–1038 (1998).
2. Perlmutter, S. *et al.* Measurements of omega and lambda from 42 high-redshift supernovae. *Astrophys. J.* **517**, 565–586 (1999).
3. Nomoto, K., Thielemann, F.-K. & Yokoi, K. Accreting white dwarf models of Type I supernovae. III. Carbon deflagration supernovae. *Astrophys. J.* **286**, 644–658 (1984).
4. Hillebrandt, W. & Niemeyer, J. C. Type Ia supernova explosion models. *Annu. Rev. Astron. Astrophys.* **38**, 191–230 (2000).
5. Whelan, J. & Iben, I. Jr. Binaries and supernovae of type I. *Astrophys. J.* **186**, 1007–1014 (1973).
6. Nomoto, K. Accreting white dwarf models for type I supernovae. I. Presupernova evolution and triggering mechanisms. *Astrophys. J.* **253**, 798–810 (1982).
7. Iben, I. Jr & Tutukov, A. V. Supernovae of type I as end products of the evolution of binaries with components of moderate initial mass (*M* not greater than about 9 solar masses). *Astrophys. J. Suppl.* **84**, 335–372 (1984).
8. Webbink, R. Double white dwarfs as progenitors of R Coronae Borealis stars and type I supernovae. *Astrophys. J.* **277**, 355–360 (1984).
9. van den Heuvel, E. P. J., Bhattacharya, D., Nomoto, K. & Rappaport, S. A. Accreting white dwarf models for CAL 83, CAL 87 and other ultrasoft X-ray sources in the LMC. *Astron. Astrophys.* **262**, 97–105 (1992).
10. Piersanti, L., Gagliardi, S., Iben, I. Jr & Tornambé, A. Carbon–oxygen white dwarf accreting CO-rich matter. II. Self-regulating accretion process up to the explosive stage. *Astrophys. J.* **598**, 1229–1238 (2003).
11. Saio, H. & Nomoto, K. Inward propagation of nuclear-burning shells in merging C–O and He white dwarfs. *Astrophys. J.* **500**, 388–397 (1998).
12. Han, Z. & Podsiadlowski, P. The single-degenerate channel for the progenitors of type Ia supernovae. *Mon. Not. R. Astron. Soc.* **350**, 1301–1309 (2004).
13. Yungelson, L. R. in *White Dwarfs: Cosmological and Galactic Probes* (eds Sion, E., Vennes, S. & Shipman, H.) 163–173 (Springer, Dordrecht, 2005).
14. Mannucci, F., Della Valle, M. & Panagia, N. Two populations of progenitors for type Ia supernovae? *Mon. Not. R. Astron. Soc.* **370**, 773–783 (2006).
15. Scannapieco, E. & Bildsten, L. The type Ia supernova rate. *Astrophys. J.* **629**, 85–88 (2005).
16. Leonard, D. C. Constraining the type Ia supernova progenitor: The search for hydrogen in nebular spectra. *Astrophys. J.* **670**, 1275–1282 (2007).
17. Mattila, S. *et al.* Early and late time VLT spectroscopy of SN 2001el—progenitor constraints for a type Ia supernova. *Astron. Astrophys.* **443**, 649–662 (2005).
18. Ruiz-Lapuente, P. The binary progenitor of Tycho Brahe's 1572 supernova. *Nature* **431**, 1069–1072 (2004).
19. Pollas, C. & Klotz, A. Supernova 2007on in NGC 1404. *Central Bureau Electronic Telegrams* **1121** (2007).
20. Gal-Yam, A. *et al.* SN 2007on is probably a young type Ia event. *Astron. Tel.* **1263** (2007).
21. Tonry, J. L. *et al.* The SBF survey of galaxy distances. IV. SBF magnitudes, colors, and distances. *Astrophys. J.* **546**, 681–693 (2001).
22. Immler, S. *et al.* Swift observations of SN 2007on. *Astron. Tel.* **1261** (2007).
23. Hamuy, M. *et al.* The absolute luminosities of the Calan/Tololo type IA supernovae. *Astron. J.* **112**, 2391–2397 (1996).
24. Bregman, J. N., Temi, P. & Bregman, J. D. The ages of elliptical galaxies from infrared spectral energy distributions. *Astrophys. J.* **647**, 265–275 (2006).
25. Li, Z., Han, Z. & Zhang, F. Potential of colors for determining age and metallicity of stellar populations. *Astron. Astrophys.* **464**, 853–857 (2007).
26. Cowley, A. P. *et al.* Six supersoft X-ray binaries: System parameters and twin-jet outflows. *Astrophys. J.* **504**, 854–865 (1998).
27. Yoon, S.-C., Podsiadlowski, P. & Rosswog, S. Remnant evolution after a carbon–oxygen white dwarf merger. *Mon. Not. R. Astron. Soc.* **380**, 933–948 (2007).
28. Tutukov, A. V. & Yungelson, L. R. Double-degenerate semidetached binaries with helium secondaries: cataclysmic variables, supersoft X-ray sources, supernovae and accretion-induced collapses. *Mon. Not. R. Astron. Soc.* **280**, 1035–1045 (1996).
29. Luna, G. J. M. & Sokoloski, J. L. The nature of the hard-X-ray emitting symbiotic star RT Cru. *Astrophys. J.* **671**, 741–747 (2007).

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