No surviving evolved companions of the progenitor of SN 1006

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Type Ia supernovae are thought to occur when a white dwarf made of carbon and oxygen accretes sufficient mass to trigger a thermonuclear explosion7. The accretion could be slow, from an unevolved (main-sequence) or evolved (subgiant or giant) star2, 3 (the single-degenerate channel), or rapid, as the primary star breaks up a smaller orbiting white dwarf4, 5 (the double-degenerate channel). A companion star will survive the explosion only in the single-degenerate channel4. Both channels might contribute to the production of type Ia supernovae6, 7, but the relative proportions of their contributions remain a fundamental puzzle in astronomy. Previous searches for remnant companions have revealed one possible case for SN 1572 (refs 8, 9), although that has been questioned10. More recently, observations have restricted surviving companions to be small, main-sequence stars11–13, ruling out giant companions but still allowing the single-degenerate channel. Here we report the results of a search for surviving companions of the progenitor of SN 1006 (ref. 14). None of the stars within 4 arc minutes of the apparent site of the explosion is associated with the supernova remnant, and we can firmly exclude all giant and subgiant stars from being companions of the progenitor. In combination with previous results, our findings indicate that fewer than 20 per cent of type Ia supernovae occur through the single-degenerate channel.

Together with SN 1572 (Tycho Brahe’s supernova), SN 1604 (Kepler’s supernova) and the recently identified SN 185, SN 1006 is one of only four known historical Galactic type Ia supernova events. It is also the only one whose type has never been disputed. Whereas a survey of the stars close to the centre of Tycho’s supernova remnant (SNR) produced a likely candidate for the companion15, and the supernova may thus be attributed to accretion via the single-degenerate channel, the absence of a surviving companion in the supernova remnant SNR 0509-67.5, in the Large Magellanic Cloud, down to very faint magnitudes, strongly suggests that the supernova there was the result of accretion via the double-degenerate channel15. Although the aforementioned direct searches have excluded, up to now, red giant companions, there is some evidence from nearby spiral galaxies that a fraction of type Ia supernovae may have had companions of this type16. This hypothesis, however, is challenged by the absence of ultraviolet emission, which would be expected at the beginning of the supernova outburst17.

The distance to the remnant of SN 1006 (2.18 ± 0.08 kpc away, as determined from the expansion velocity and the proper motion of the ejecta18) is much more precisely known than that of the remnant of SN 1572 (2.83 ± 0.70 kpc). The interstellar extinction is also much smaller, which makes the distances to the stars less uncertain. To be a possible candidate, a star must be at the correct distance and, depending on its spectral type and luminosity class, must show some spectral peculiarity or an enhancement of the abundances of Fe-peak elements such as that seen in star G of Tycho’s supernova17. Because of its relative proximity compared with SN 1572, and the lower extinction (V-band extinction of AV = 0.3 mag, versus 2.0–2.4 mag in Tycho’s supernova), going down to an R-band magnitude of mR = 15 mag allows us to include, out to the supernova distance and beyond, all red giants, giant stars and main-sequence stars11–13, ruling out giant companions but still allowing the single-degenerate channel. Here we report the results of a search for surviving companions of the progenitor of SN 1006 (ref. 14). None of the stars within 4 arc minutes of the apparent site of the explosion is associated with the supernova remnant, and we can firmly exclude all giant and subgiant stars from being companions of the progenitor. In combination with previous results, our findings indicate that fewer than 20 per cent of type Ia supernovae occur through the single-degenerate channel.

Figure 1 | R-band image of the SN 1006 field. Image from the Digitized Sky Survey 2. The positions and names of the 26 stars included in the spectroscopic survey (selected from the USNO-A2.0 catalogue19) are given. The centre of our search is the geometrical centre of the quite symmetrical X-ray emission of the SNR22 (green cross), at RA = 15 h 2 min 55 s, dec. = −41° 55’ 12”. Also shown are the boundary of the surveyed region (large green circle) and the geometrical centre of the Hα emission19 (small yellow circle). Giant stars are marked by red squares. See also Supplementary Fig. 1, for a full view of the SNR. Another centre has been proposed more recently20, on the basis of the distribution of the ejecta along the line of sight. It is, however, still located within our surveyed area. For a star at a distance of d = 2.2 kpc and with a velocity of ~100 km s−1 (roughly the orbital velocity before the explosion) perpendicular to the line of sight, the angular displacement on the sky in 1,000 yr would be only 10″. However, given the asymmetry of the SNR, and also that in core-collapse supernovae the distance between the compact object and the X-ray centroid of the SNR can be 15% or more of the radius of the SNR, we adopted a much wider area. For a star at a distance of d = 2.2 kpc and with a velocity of ~100 km s−1 (roughly the orbital velocity before the explosion) perpendicular to the line of sight, the angular displacement on the sky in 1,000 yr would be only 10″. However, given the asymmetry of the SNR, and also that in core-collapse supernovae the distance between the compact object and the X-ray centroid of the SNR can be 15% or more of the radius of the SNR, we adopted a much wider radius for the search: 4′. That amounts to 27% of the radius of the SNR, which is 15′ (Supplementary Fig. 1). Positions, magnitudes and angular distances to the centre of the survey are given in Supplementary Table 1.

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In Supplementary Fig. 3, we also show the Galactic trends of several

the number of atoms of element X and the second logarithm involves

search.

We derive the stellar atmosphere parameters of the sample stars (Fig. 1) using high-resolution spectroscopic data from the Ultraviolet and Visual Echelle Spectrograph (UVES) (Table 1). The spectra of four giants in the sample are shown in Fig. 2, and those of F- and G-type dwarfs are shown in Supplementary Fig. 2. In Table 1, we also provide the radial velocities of sample stars measured from the UVES spectra, and distances determined from five photometric magnitudes, taking into account the stellar parameters (Supplementary Information). In Fig. 3, we compare the abundances of Fe-peak elements in the stars of our sample with the Galactic trends, for F-, G- and K-type unevolved stars. Unlike in SN 1572, where star G shows an overabundance of Ni ([Ni/Fe] = log(Ni/NFe) − log(NFe/NFe)) = 0.16 ± 0.04, where NFe is the number of atoms of element Fe and the second logarithm involves solar values), the stars in SN 1006 are all within the dispersion of the Galactic [Ni/Fe] trend. No enhancement is seen for any other element. In Supplementary Fig. 3, we also show the Galactic trends of several α-elements and we do not see any clear anomaly in these element abundances either.

None of the stars in the sample shows any noteworthy rotation. High rotation speeds have been claimed to be a characteristic of the surviving companions of type Ia supernovae, on the assumptions that, first, owing to tidal interaction and in spite of the angular momentum loss due to mass transfer, the rotation periods before explosion are equal to the (short) orbital periods, and, second, the radius of the star remains basically unchanged after the explosion. It has recently been shown, however, that in a type Ia supernova the impact of the ejecta on the companion does indeed reduce those speeds by a large factor, which would make the rotation criterion irrelevant.

Only four stars are at distances (marginally) compatible with that of the remnant of SN 1006. All of them are red giants: B16564 (G9-K0 III), B97341 (G9 III), B99810 (K1 III) and B93571 (K1 III) and none shows any spectroscopic peculiarity.

Two-dimensional hydrodynamic simulations of the impact of the ejecta of a type Ia supernova on a red giant binary companion have been performed. More recently, the emission of supernova debris, arising from their impact with a similar companion, has been also considered. In terms of the effects of the explosion on the companion.
star, the results agree: most of the envelope is stripped away and what is left are the degenerate core and a very small fraction (amounting to a few per cent) of the original envelope. This hydrogen-rich envelope initially extends out to a radius of \( \sim 350 \) solar radii and then contracts on a thermal timescale. The star should be evolving at constant luminosity (of about 1,000 times the solar luminosity) towards increasing effective temperatures for \( 10^9 \)–\( 10^{10} \) yr. The same conclusion is reached when extrapolating to the red giant case the results of simulations of the impact of type Ia supernova ejecta on a main-sequence companion\(^{22}\): the red giant should have been stripped of most of its hydrogen envelope.

Nothing similar to any of the above four normal red giants would be seen. However, the peculiar type of object that would result from the interaction of the ejecta with a red giant companion would be luminous enough to have been seen at the distance of SN 1006 and within our magnitude limit. A subgiant star similar to star G in Tycho’s supernova would equally have been seen, but the only three subgiants in the sample (B20292, B15360 and B14707) lie much closer than the SNR. We are thus left with only main-sequence stars, which lie at shorter distances than the SNR; have luminosities similar to, or lower than, the solar luminosity; and are not predicted by any of the hydrodynamic simulations of the impact of type Ia supernova ejecta with either a main-sequence star or a subgiant. In these hydrodynamic simulations\(^{22}\), a main-sequence companion of one solar mass is expanded and heated, reaching \( \sim 5,000 \) times the solar luminosity; it is then predicted to cool down on a thermal timescale. It has been found that the return to luminosities of the order of those before the explosion could be faster because of the short cooling times of the outermost layers of the star\(^4\), but, even so, in only \( \sim 1,000 \) yr the object does not have enough time to become dimmer than the Sun (Supplementary Information).

Accordingly, SN 1006, the brightest event so far observed in our Galaxy, should have been produced either by mass accretion from an unevolved star similar to, or less massive than, the Sun (with the above caveats), or by merging with another white dwarf. Adding this result to the evidence from the other direct searches, the single-degenerate channel seems either to encompass only a clear minority of cases (20% or fewer) or preferentially involves main-sequence companions with masses more probably below that of the Sun.

**Figure 3 | Stellar abundance ratios \([X/Fe]\) of several Fe-peak elements.** The chemical abundances have been derived using the equivalent-width technique for each element: chromium (a), manganese (b), cobalt (c) and nickel (d). We performed a differential analysis on a line-by-line basis, using the solar UVES spectrum of the Moon as reference (see Supplementary Information, section 3, for more details). The abundances of several Fe-peak elements relative to iron (Supplementary Table 4b) are compared with the Galactic trends of these elements (black circles) in the relevant range of metallicities\(^{20}\). Red triangles correspond to the four giant stars whose distances are marginally compatible with that of the remnant of SN 1006. Blue squares correspond to the rest of the stars in the sample. The error bars are the 1\( \sigma \) uncertainties associated with the dispersion of the measurements from different spectral features.

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

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