The binary progenitor of Tycho Brahe’s 1572 supernova

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The brightness of type Ia supernovae, and their homogeneity as a class, makes them powerful tools in cosmology, yet little is known about the progenitor systems of these explosions. They are thought to arise when a white dwarf accretes matter from a companion star, is compressed and undergoes a thermonuclear explosion\(^1\)\(^{-3}\). Unless the companion star is another white dwarf (in which case it should be destroyed by the mass-transfer process itself), it should survive and show distinguishing properties. Tycho’s supernova\(^4\)\(^{-5}\) is one of the only two type Ia supernovae observed in our Galaxy, and so provides an opportunity to address observationally the identification of the surviving companion. Here we report a survey of the central region of its remnant, around the position of the explosion, which excludes red giants as the mass donor of the exploding white dwarf. We found a type G0–G2 star, similar to our Sun in surface temperature and luminosity (but lower surface gravity), moving at more than three times the mean velocity of the stars at that distance, which appears to be the surviving companion of the supernova.

Tycho Brahe’s supernova (that is, SN 1572) is one of the only two supernovae observed in our Galaxy that are thought to have been of type Ia (the other having been SN 1006) as revealed by the light curve, radio emission and X–ray spectra\(^4\)\(^{-7}\).

The field that contained Tycho’s supernova, relatively devoid of background stars, is favourable for searching for any surviving companion. With a Galactic latitude \(b = +1.4^\circ\), Tycho’s supernova lies 59–78 pc above the Galactic plane. The stars in that direction show a consistent pattern of radial velocities with a mean value of \(-30\) km s\(^{-1}\) at 3 kpc. The predictions of how the companion star would look after the impact, if there is any companion, depend on what the star actually is. The star could be in any evolutionary stage before the explosion: main sequence, subgiant or red giant\(^1\)\(^{-3}\). The most salient
feature of the surviving companion star should be peculiar velocities with respect to the average motion of the other stars at the same location in the Galaxy (mainly due to disruption of the binary)\(^8\), detectable through radial–velocity measurements, and perhaps also signs of the impact of the supernova ejecta. The latter can be twofold. First, mass should have been stripped from the companion and thermal energy injected into it, possibly leading to expansion of the stellar envelope that would make the star have a lower surface gravity. Second, depending on the interaction with the ejected material, the surface of the star could be contaminated by the slowest–moving ejecta (made of Fe and Ni isotopes). If the companion’s stellar envelope is radiative, such a contamination could be detectable through abundance measurements. Therefore, the observations have been designed along these lines. The star most likely to have been the mass donor of SN 1572 has to show a multiple coincidence: being at the distance of SN 1572, it has to show an unusual radial velocity in comparison to the stars at the same location (much above the velocity dispersion for its spectral type), and have stellar parameters consistent with being struck by the SN explosion. It should also lie near the remnant centre (that is, within our search radius).

The distance to SN 1572 inferred from the expansion of the radio shell and by other methods lies around 3 kpc (2.83 ± 0.79 kpc)\(^9\). Such a distance, and the light–curve shape of SN 1572, are consistent with it being a normal type Ia supernova in luminosity, as those commonly found in cosmological searches\(^9\). Given the age of the supernova remnant (SNR; just 432 yr) and the lower limit to its distance, any possible companion, even if it moved at a speed of 300 km s\(^{-1}\), could not be farther than 0.15 arcmin (9.1 arcsec) from its position at the time of the explosion\(^8,10\). But the search radius significantly expands owing to the uncertainty in the derived centre of the SNR (see Fig. 1).

We have analysed the stars within a circle of 0.65 arcmin radius, centred on the Chandra X-ray Observatory coordinates for the centre of the SNR, up to an apparent visual
magnitude $V = 22$ (Figure 1, Figure 2, Table 1, and Supplementary Tables 1–3).

All but one of the stars found are either main-sequence stars (luminosity class V) with spectral types A4–K3 or giant stars (luminosity class III) with spectral types G0–K3. Red–giant stars are possible companions of type Ia supernovae. Masses in the range 0.9–1.5 solar masses (0.9–1.5 $M_\odot$) would be the most favourable cases\textsuperscript{11}. Red giants are well represented in the sample, but none of them passes the tests for being a viable candidate. They are at distances incompatible with that of the supernova. The only giant relatively close to the distance of SN 1572 is Tycho A (Fig. 3), but it is closer than SN 1572 and shows no peculiarities in velocity, spectral type, or metallicity. Main-sequence stars are also viable companions of type Ia supernovae. Close binaries with 2 to 3.5 $M_\odot$ main–sequence or subgiant companions have indeed been suggested as one class of systems able to produce type Ia supernovae\textsuperscript{12}. Among systems containing a main–sequence star, recurrent novae have been pointed out as possible progenitors\textsuperscript{13}. Stripping of mass from the impact of the ejecta on this type of companion is also expected\textsuperscript{8,14}. Another consequence of the impact should be to puff up the star and dramatically increase its luminosity. The size and luminosity would later return to their equilibrium values for a star with the new decreased mass\textsuperscript{8,14,15}. Peculiar velocities should be highest (200–300 km s$^{-1}$) in the case of main–sequence companions (orbital separations at the time of explosion are shortest), but the measured values of radial velocity ($v_r$) for the main–sequence stars observed are not particularly high. The surface abundances are compatible with solar values. Other main–sequence stars (see Fig. 1, Table 1 and Supplementary Table 3) are found at wider separations from the geometrical centre, but they have $v_r$ values within the range corresponding to their respective distances (see Supplementary Discussion).

We have found a subgiant star (‘Tycho G’) with lower surface gravity than that of main–sequence stars but higher surface gravity than that of red giants, which moves fast in
comparison to the mean radial velocities of stars around it, and fits well the expectations for distance, reddening and velocity. Comparison of the Tycho G spectrum covering a wide wavelength range (3,180–9,400 Å) with templates\textsuperscript{16}, after dereddening by $E(B - V) \approx 0.6$ mag, gives a best fit for an effective temperature $T_{\text{eff}} = 5750$ K, a surface gravity $\log g$ between 4.0 and 3.0, and solar metallicity, which is confirmed by model fitting to high–resolution spectra in selected wavelength ranges (see Fig. 3, Supplementary Fig. 1). For the spectral type found (G0–G2) and being a slightly evolved star (surface gravity not much below the main–sequence value), the mass should be about solar ($M \approx 1 M_\odot$) and thus the radius, for the range of surface gravities above, should be $R \approx 1–3 R_\odot$, which translates (via our photometric data) into a distance $d \approx 2.5–4.0$ kpc. This companion could have been a main–sequence star or a subgiant before the explosion. While main–sequence companions might no longer look like ordinary main–sequence stars after the explosion of the type Ia supernova (and they might resemble subgiants, their envelopes having expanded after the supernova impact), subgiants would remain subgiants of lower surface gravity\textsuperscript{9,10,14,15}.

Stars at distances $d \approx 2–4$ kpc, in that direction, are moving at average radial velocity\textsuperscript{17} $v_r \approx -20$ to $-40$ km s$^{-1}$ (in the Local Standard of Rest), with a $\sim 20$ km s$^{-1}$ velocity dispersion\textsuperscript{18,19}. Tycho G moves at $-108 \pm 6$ km s$^{-1}$ (heliocentric) in the radial direction. The deviation of Tycho G from the average thus exceeds by a factor of 3 the velocity dispersion of its stellar type. It has a 0.3\% probability of having that characteristic and being unrelated to the explosion (that is, it is a $3\sigma$ outlier). In contrast, all other stars with distances compatible with that of SN 1572 have radial velocities within the velocity dispersion as compared with the average of all stars at the same location in the Galaxy. We studied through detailed proper motion measurements on the HST WFPC2 images\textsuperscript{20} whether Tycho G has a high tangential velocity as well (see Supplementary Table 2 and Supplementary Methods). Tycho G has significant proper motion toward lower
Galactic latitude: $\mu_b = -6.11 \pm 1.34 \text{ mas yr}^{-1}$ (the proper motion along longitude is small, $\mu_l = -2.6 \pm 1.34 \text{ mas yr}^{-1}$). The proper motion in Galactic latitude implies that this star is an outlier in proper motion as well, with a derived tangential velocity of $94 \pm 27 \text{ km s}^{-1}$ (a $24 \text{ km s}^{-1}$ systematic error was added, resulting from a $1.7 \text{ mas yr}^{-1}$ uncertainty in the reference frame solution of the images). The other stars do not show such coincidence in distance and high tangential velocity. The modulus of the velocity vector has a value of $136 \text{ km s}^{-1}$, which is over a factor of 3 larger than the mean velocity value at 3 kpc.

If Tycho G is the companion star as suggested by its kinematics, the explosion centre should have been 2.6 arcsec north of the current location of this star on the basis of its velocity. The peculiar velocity would correspond to the peculiar velocities expected from the disruption of a white dwarf plus subgiant/main–sequence system$^9,10$ of roughly a solar mass. The system would have resembled the recurrent nova U Scorpii (see Supplementary Note 2). The excess velocity corresponds to a period of about 2–7 days, for a system made of a white dwarf close to the Chandrasekhar mass plus a companion of roughly a solar mass at the moment of the explosion.

Several paths lead to this star as the likely donor star of SN 1572: its high peculiar velocity (both radial and tangential velocities), the distance in the range of SN 1572, and its type, which fits the post–explosion profile of a type Ia supernova companion, as the position of this star in the Hertzsprung–Russell diagram is also untypical for a standard subgiant. The lower limit to the metallicity obtained from the spectral fits is $[\text{M/H}] > -0.5$ (see Fig. 3 and Supplementary Fig. 1), which excludes its belonging to the Galactic halo population as an alternative explanation of its high velocity. Spectra taken at five different epochs also exclude its being a single–lined spectroscopic binary. If our candidate is the companion star, its overall characteristics imply that the supernova explosion would affect the companion mainly through the kinematics. Our search for the binary companion of
Tycho’s supernova has excluded giant stars. It has also shown the absence of blue or highly luminous objects as post-explosion companion stars. A star very similar to the Sun but of a slightly more evolved type is here suggested as the likely mass donor that triggered the explosion of SN 1572. That would connect the explosion to the family of cataclysmic variables.
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FIGURE CAPTIONS

Figure 1 Positions and proper motions of stars. Positions are compared with three centres: the Chandra (Ch) and ROSAT (RO) geometrical centres of the X-ray emission, and that of the radio emission (Ra). Dashed lines indicate circles of 0.5 arcmin around those centres. The supernov position reconstructed from Tycho Brahe’s measurements (Ty) is also shown, though merely for its historical interest. The radius of the remnant is about 4 arcmin and the SNR is quite spherically symmetric, with a fairly good coincidence between radio and continuum X-ray emission. However, there is a 0.56 arcmin displacement along the east–west axis between the radio emission and the high–energy continuum in the 4.5–5.8 keV band observed by XMM–Newton in the position of the western rim (Supplementary Note 1). Such asymmetry amounts to a 14% offset along the east–west axis. In SNRs from core–collapse supernovae (type II supernovae), up to a 15% discrepancy between the location of the compact object and the geometric center is found in the most symmetric cases. On the basis of the above considerations, in our search we cover 15% of the innermost radius (0.65 arcmin) of the SNR around the Chandra centre of SN 1572. The companion star, if there is any, is unlikely to be outside this area (solid line). The proper motions of the stars measured from HST WFPC2 images are represented by arrows, their lengths indicate the total displacements between AD 1572 and present. Error bars are shown by parallel segments. Red circles are the extrapolated positions of the stars back to AD 1572. Star Tycho G displays a high proper motion, corresponding to the highest tangential velocity in the field, since both stars U and O are at much shorter distances (see Supplementary Methods).

Figure 2 The SN 1572 field and radial velocity of the stars. a, Image from the Auxiliary Port at the William Herschel Telescope. It confirms the relative emptiness of the field. The search area (see also Fig. 1 bold circle) covers a radius of 0.65 arcmin around RA
= 00 h 25 min 19.9 s, dec. = 64° 08′ 18.2″ (J2000) (the Chandra geometrical centre of X–ray emission) with repeated photometric and spectroscopic observations of the included stars at various epochs to check for variability and exclude binarity. Additional stars have been observed outside of the 0.65 arcmin radius area and are visible in this field (whose diameter is 1.8 arcmin). For a remnant distance $d = 3.0$ kpc and a visual extinction $A_V = 1.7 - 2.0$ mag toward the candidate stars (see Supplementary Table 3), our search limit down to an apparent visual magnitude $V = 22$ implies that the survey must have detected all main–sequence stars of spectral types earlier than K6, plus all subgiant, giant and supergiant stars within the corresponding cone. At that distance and with such extinction, the Sun would shine as a $V = 18.9$ mag star. 

b, Radial velocity (in the Local Standard of Rest, LSR) versus distance for the subsample of stars closer than 6.5 kpc (the other stars are at a distance well beyond the SNR). We are looking outward along the Galactic plane, and the dashed line shows the approximate relationship for the stars in the direction of Tycho given by the expression $v_r = -v_\odot \cos(l - l_\odot) + A r \sin(2l)$, where $l$ and $l_\odot$ are the respective Galactic longitudes of Tycho and the solar apex, $v_\odot$ is the Sun’s velocity in the LSR, and $A$ is Oort’s constant$^{18}$. We include two field stars (stars O and U) that are slightly away from the search area (at >15% of the radius of the SNR) but at distances in the range 2–4 kpc as well. (Star names are labelled lower case in a for clarity.)

Figure 3 Model fits to observed spectra. Model atmosphere parameters are those listed in Table 1, and chemical abundances are solar. They are shown here for our candidate star for the companion of SN 1572 (Tycho G) and the red giant (Tycho A) and main–sequence star (Tycho B) nearest to the distance of SN 1572 and to the X–ray centre. Identifications of the most significant metal lines are given. We have not detected significant spectroscopic anomalies, either here or in the whole sample, and most spectra are well reproduced assuming solar abundances$^{25}$. Thin lines correspond to the observations and thicker lines
to the synthetic spectra. Spectra were obtained at the William Herschel Telescope (WHT) with UES and ISIS. Tycho A (bottom panel) is the closest red giant in the sample. It is a K0 III star, and its mass should be typically $M \approx 3 \, M_\odot$ ($M_\odot$ stands for the mass of the Sun). Here, Tycho A is ruled out simply on the basis of having too short a distance. All the other red giants are located well beyond Tycho’s remnant, and therefore also ruled out (see Supplementary Discussion). The A8/A9 star Tycho B (second panel from bottom) has $M \approx 1.5 \, M_\odot$, which would fall within the appropriate range for main–sequence type Ia supernova companions, as it would have been massive enough to transfer the required amount of mass to the WD. The entirely normal atmospheric parameters, however, strongly argue against any such event in the star’s recent past. The low radial velocity reinforces this conclusion. Tycho G (three upper panels). The second and third spectra from the top show computed spectra compared with observed spectra obtained at the WHT with ISIS. The upper panel shows the observed spectrum near Hα. This line is blueshifted, implying a peculiar radial velocity exceeding about 3 times the velocity dispersion for its stellar type. This star does not belong to the halo population (Supplementary Fig. 1).
TABLE CAPTION

Supernova companion candidates within the search radius and limiting magnitude. Angular distances $\theta$ are from the Chandra X-ray geometrical centre, located at RA = 00 h 25 min 19.9 s, dec. = 64° 08′ 18.2″ (J2000). Synthetic spectra, under the assumption of local thermodynamic equilibrium (LTE), are fitted to the observed ones using the grids of model atmospheres and the atomic data of Kurucz$^{25}$, with the Uppsala Synthetic Spectrum Package$^{27}$. This determines the atmospheric parameters effective temperature $T_{\text{eff}}$ and surface gravity $g$. Intrinsic colours and absolute visual magnitudes are deduced from the relationships between spectral type and colour and between spectral type and absolute magnitude for the different luminosity classes$^{28}$. Comparison with our photometric $BVR$ measurements (see Supplementary Table 3) yields the reddening $E(B - V)$, from which the visual extinction $A_V$ and the corrected apparent visual magnitude $V_0$ are calculated. Comparison with the absolute visual magnitude then gives the distance $d$. Uncertainties in $T_{\text{eff}}$ are 250 K. Tycho J is a binary of main–sequence stars with masses in the range 0.80–0.85 $M_\odot$ and quite similar atmospheric parameters. Tycho C is found in HST images as being two stars (C1 and C2) 0.25 arcsec apart. Modelling of the composite spectrum and the HST magnitudes of the stars show that they do not constitute a physical binary; the hot fainter component C2 is at larger distance than C1. Within this list of stars, D, G, N and V have proper motions along Galactic longitude and latitude of $\mu_l = -3.23$, $\mu_b = -0.58 \pm 0.66$ (same error in both coordinates, units in mas yr$^{-1}$) for star D, $\mu_l = -2.60$, $\mu_b = -6.11 \pm 1.34$ for star G, $\mu_l = 3.23$, $\mu_b = 1.45 \pm 1.15$ for star N, and $\mu_l = 1.61$, $\mu_b = -2.85 \pm 0.78$ for star V.
Table 1: Table 1. Characteristics of the supernova companion candidates

| Star   | θ  | Spec. type & lum. class | T\textsubscript{eff} (K) | log g (c.g.s.) | E(B–V) (mag.) | d (kpc) |
|--------|----|------------------------|--------------------------|----------------|---------------|--------|
| Tycho A | 1.6 | K0–K1 III | 4750 | 2.5\textsuperscript{+0.5}_{-0.5} | 0.55\textsuperscript{+0.05}_{-0.05} | 1.1\textsuperscript{+0.3}_{-0.3} |
| Tycho B | 1.5 | A8–A9 V | 7500 | 4.5\textsuperscript{+0.5}_{-0.5} | 0.60\textsuperscript{+0.05}_{-0.05} | 2.6\textsuperscript{+0.5}_{-0.5} |
| Tycho C1 | 6.5 | K7 V | 4000 | 4.5\textsuperscript{+0.5}_{-0.5} | 0.5\textsuperscript{+0.1}_{-0.1} | 0.75\textsuperscript{+0.5}_{-0.5} |
| Tycho C2 | 6.5 | F9 III | 6000 | 2.0\textsuperscript{+0.5}_{-0.5} | 0.6\textsuperscript{+0.1}_{-0.1} | > 20 |
| Tycho D | 8.4 | M1 V | 3750 | 4.5\textsuperscript{+0.5}_{-0.5} | 0.6\textsuperscript{+0.3}_{-0.3} | 0.8\textsuperscript{+0.3}_{-0.2} |
| Tycho E | 10.6 | K2–K3 III | 4250 | 2.0\textsuperscript{+0.5}_{-0.5} | 0.60\textsuperscript{+0.10}_{-0.10} | > 20 |
| Tycho F | 22.2 | F9 III | 6000 | 2.0\textsuperscript{+0.5}_{-0.5} | 0.54\textsuperscript{+0.22}_{-0.22} | > 10 |
| Tycho G | 29.7 | G2 IV | 5750 | 3.5\textsuperscript{+0.5}_{-0.5} | 0.60\textsuperscript{+0.05}_{-0.05} | 3.0\textsuperscript{+1.0}_{-0.5} |
| Tycho H | 30.0 | G7 III | 5000 | 3.0\textsuperscript{+0.5}_{-0.5} | 0.60\textsuperscript{+0.09}_{-0.09} | > 13 |
| Tycho J | 33.9 | K1 V | 5000 | 4.5\textsuperscript{+0.5}_{-0.5} | 0.58\textsuperscript{+0.12}_{-0.11} | 2.4\textsuperscript{+0.3}_{-0.2} |
| Tycho K | 35.0 | F9 III | 6000 | 2.0\textsuperscript{+0.5}_{-0.5} | 0.60\textsuperscript{+0.10}_{-0.10} | > 10 |
| Tycho N | 35.4 | G0 V | 6000 | 4.5\textsuperscript{+0.5}_{-0.5} | 0.62\textsuperscript{+0.08}_{-0.07} | 2.1\textsuperscript{+0.7}_{-0.7} |
| Tycho V | 29.2 | K3 V | 4750 | 4.5\textsuperscript{+0.5}_{-0.5} | 0.60\textsuperscript{+0.10}_{-0.10} | 3.8\textsuperscript{+0.6}_{-0.6} |
WHT Aux Port
Filter B, 600s
15 June 2002

Fig. 2—
Fig. 3.—
Supplementary Information

Supplementary Methods Specification of the WFPC2 measurements

Supplementary Table 1 Spectroscopic runs at the 4.2 m William Herschel Telescope (WHT), the 2.5 m Nordic Optical Telescope (NOT) and the 10 m Keck I and Keck II telescopes used in this work

Supplementary Table 2 Hubble Space Telescope data sets used for proper motions measurements

Supplementary Table 3 Magnitudes and radial velocities of the stars

Supplementary Note 1 Note on the origin of the asymmetry in Tycho SNR

Supplementary Discussion Further discussion on red giant and main sequence stars

Supplementary Figure 1 Spectra of Tycho G showing it to be a subgiant not belonging to the halo population

Supplementary Note 2 Tycho Brahe SN as a U Sco system
Supplementary Methods

Specification of the WFPC2 measurements

The proper motions were calculated by comparing through a maximum likelihood analysis the displacement in image centroids of the target stars to a reference frame determined from all the point sources in common between the WFPC2 images of the two epochs\(^1\).

For the majority of our targets, the stellar images fell on the WF3 CCD of the WFPC2 mosaic camera on both epochs. However, due to differences in the camera pointing and roll-angle between the exposures at the two epochs, the target star K fell on different CCDs of the WFPC2 mosaic at the two epochs, as did the stars L, M, and W (these three not being targets). The overlap region proved to be too small to determine a reference frame, and so the proper motions of these stars could not be measured. A similar effect entered the measurement of target H, which had to be done using images spanning a shorter time baseline, and making the uncertainty too large. No accurate image centroids were derived for the stars C1 and C2 due to their small separation, neither for Target A which is saturated in the reference images and has a background star at half a second of its centroid. The other stars do not have significant proper motions (at \(> 2\sigma\)). This proper motion programme continues in \textit{HST} Cycle 13 where measurements with smaller error bars will be obtained using both WFPC2 and ACS.

\(^1\) Ibata, R. A. & Lewis, G. F., Proper motion measurements with WFPC. Astron. J, 116, 2569 (199
### Supplementary Table 1. Spectroscopic runs in this work

| Date       | Telescope | Instrument/Grating | Resolution | Coverage (Å) |
|------------|-----------|--------------------|------------|--------------|
| 1997-12-04 | WHT       | ISIS+R158B/R158R   | 600        | 3200–9000    |
| 1998-01-03 | WHT       | ISIS+R300B/R158R   | 1700–600   | 3200–9000    |
| 1999-02-24 | WHT       | ISIS+R300B/R158R   | 1700–600   | 3200–9000    |
| 2000-11-21 | Keck I    | ESI                | 10000–7000 | 4000–10000   |
| 2001-06-16 | WHT       | UES                | 50000      | 4000–7100    |
| 2001-06-17 | WHT       | ISIS+H2400B/R1200R | 10000–7000 | 4000–7000    |
| 2002-06-12 | WHT       | ISIS+H2400B/R1200R | 10000–7000 | 4400–7000    |
| 2002-06-13 | WHT       | ISIS+H2400B/R1200R | 10000–7000 | 4400–7000    |
| 2002-06-14 | WHT       | ISIS+R300B/R158R   | 1700–600   | 3200–9000    |
| 2002-10-09 | NOT       | ALFOSC+Grism9      | 4500–3900  | 4400–9000    |
| 2002-12-05 | WHT       | ISIS+H2400B/R1200R | 10000–7000 | 4800–7000    |
| 2002-12-06 | WHT       | ISIS+H2400B/R1200R | 10000–7000 | 4400–7000    |
| 2003-07-27 | Keck II   | LRIS+300/5000      | 850        | 3200–7900    |
| 2003-07-30 | WHT       | ISIS+R1200B/R1200R | 7000       | 4000–7000    |
| 2003-07-31 | WHT       | ISIS+R1200B/R1200R | 7000       | 4000–7000    |
| 2003-11-16 | WHT       | ISIS+R1200B/R1200R | 7000       | 4000–7000    |
| 2003-11-17 | WHT       | ISIS+R1200B/R1200R | 7000       | 4000–7000    |
| 2003-11-18 | WHT       | ISIS+R1200B/R1200R | 7000       | 4000–7000    |
| 2003-12-20 | Keck I    | LRIS+150/7500      | 500        | 3156–9400    |

Spectroscopic runs at the 4.2 m William Herschel Telescope (WHT), the 2.5 m Nordic Optical Telescope (NOT) and the 10 m Keck I and Keck II telescopes used in this work.
**Supplementary Table 2.** Hubble Space Telescope data sets used for proper motion measurements

| Dataset     | Date       | Filter | Exposure Time | Instrument |
|-------------|------------|--------|---------------|------------|
| U8S9010HM   | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010IM   | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010JM   | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010KM   | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010LM   | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S90201M   | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90202M   | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90203M   | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90204M   | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90205M   | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90206M   | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90207M   | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90208M   | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90209M   | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S9020AM   | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S9020BM   | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020CM   | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020DM   | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020EM   | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020FM   | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| Dataset      | Date       | Filter | Exposure Time | Instrument |
|--------------|------------|--------|---------------|------------|
| U8S9010HM    | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010IM    | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010JM    | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010KM    | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S9010LM    | 2003-11-08 | F555W  | 100.0 s       | WFPC2      |
| U8S90201M    | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90202M    | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90203M    | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90204M    | 2003-11-06 | F555W  | 400.0 s       | WFPC2      |
| U8S90205M    | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90206M    | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90207M    | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90208M    | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S90209M    | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S9020AM    | 2003-11-06 | F555W  | 1.0 s         | WFPC2      |
| U8S9020BM    | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020CM    | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020DM    | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020EM    | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020FM    | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020GM    | 2003-11-06 | F555W  | 0.2 s         | WFPC2      |
| U8S9020HM    | 2003-11-06 | F555W  | 100.0 s       | WFPC2      |
| U8S9020IM    | 2003-11-06 | F555W  | 100.0 s       | WFPC2      |
| U8S9020JM    | 2003-11-06 | F555W  | 100.0 s       | WFPC2      |
| U8S9020KM    | 2003-11-06 | F555W  | 100.0 s       | WFPC2      |
| U8S9020LM    | 2003-11-06 | F555W  | 100.0 s       | WFPC2      |

**Supplementary Table 2 (cont.)** The data from 1999 correspond to *HST* programmes *GO*6435 and *GO*7405. The data from 2003 correspond to *GO*9729.
### Supplementary Table 3. Magnitudes and radial velocities of the stars

| Star | $\theta$ (arcsec) | $B$ (mag.) | $V$ (mag.) | $R$ (mag.) | $v_r$ (km/s) |
|------|-------------------|------------|------------|------------|-------------|
| A    | 1.6               | 14.82$^{+0.03}_{-0.03}$ | 13.29$^{+0.03}_{-0.03}$ | 12.24$^{+0.03}_{-0.03}$ | $-23^{+1}_{-1}$ |
| B    | 1.5               | 16.35$^{+0.03}_{-0.03}$ | 15.41$^{+0.03}_{-0.03}$ | 15.11$^{+0.10}_{-0.10}$ | $-38^{+8}_{-8}$ |
| C$^*$| 6.5               | 21.06$^{+0.12}_{-0.12}$ | 19.06$^{+0.05}_{-0.05}$ | 17.77$^{+0.03}_{-0.03}$ | $-33^{+6}_{-6}$ |
| D    | 8.4               | 22.97$^{+0.28}_{-0.28}$ | 20.70$^{+0.10}_{-0.10}$ | 19.38$^{+0.06}_{-0.06}$ | $-$ |
| E    | 10.6              | 21.24$^{+0.13}_{-0.13}$ | 19.79$^{+0.07}_{-0.07}$ | 18.84$^{+0.05}_{-0.05}$ | $-26^{+18}_{-18}$ |
| F    | 22.2              | 19.02$^{+0.05}_{-0.05}$ | 17.73$^{+0.03}_{-0.03}$ | 16.94$^{+0.03}_{-0.03}$ | $-34^{+11}_{-11}$ |
| G    | 29.7              | 20.09$^{+0.08}_{-0.08}$ | 18.71$^{+0.04}_{-0.04}$ | 17.83$^{+0.03}_{-0.03}$ | $-99^{+6}_{-6}$ |
| H    | 30.0              | 21.39$^{+0.14}_{-0.14}$ | 19.80$^{+0.07}_{-0.07}$ | 18.78$^{+0.05}_{-0.05}$ | $-71^{+10}_{-10}$ |
| J    | 33.9              | 21.15$^{+0.12}_{-0.12}$ | 19.74$^{+0.07}_{-0.07}$ | 18.84$^{+0.05}_{-0.05}$ | $-45^{+6}_{-6}$ |
| K    | 35.0              | 21.64$^{+0.15}_{-0.15}$ | 20.11$^{+0.08}_{-0.08}$ | 19.15$^{+0.05}_{-0.05}$ | $-33^{+10}_{-10}$ |
| N    | 35.4              | 19.59$^{+0.06}_{-0.06}$ | 18.29$^{+0.04}_{-0.04}$ | 17.47$^{+0.03}_{-0.03}$ | $-30^{+6}_{-6}$ |
| V    | 29.2              | 23.32$^{+0.33}_{-0.33}$ | 21.41$^{+0.13}_{-0.13}$ | 20.20$^{+0.08}_{-0.08}$ | $-47^{+10}_{-10}$ |
| O    | 41.5              | 18.65$^{+0.04}_{-0.04}$ | 17.23$^{+0.03}_{-0.03}$ | 16.37$^{+0.03}_{-0.03}$ | $-15^{+7}_{-7}$ |
| P    | 40.4              | 18.84$^{+0.10}_{-0.10}$ | 17.61$^{+0.03}_{-0.03}$ | 16.78$^{+0.03}_{-0.03}$ | $-36^{+10}_{-10}$ |
| U    | 39.5              | 19.03$^{+0.05}_{-0.05}$ | 17.73$^{+0.03}_{-0.03}$ | 16.95$^{+0.03}_{-0.03}$ | $-38^{+4}_{-4}$ |

Angular distances from Chandra’s geometrical X-ray centre, BVR apparent magnitudes and radial velocities (LSR) for the sample of SN companion candidates. Radial velocities have been measured from the wavelength shifts of several absorption lines in each observed spectrum (see Supplementary Table 1). *Data are for the unresolved pair. From the HST data, the brighter, bluer component has magnitudes B = 21.28, V = 19.38, R = 18.10 while the fainter, redder component has B = 22.91, V = 20.53, R = 19.23.
Supplementary Note 1

Note on the origin of the asymmetry in Tycho SNR

Evidence that the ejecta encountered a dense H cloud at the eastern edge giving rise to brighter emission and lower ejecta velocity there, while finding a lower-density medium in the western rim, might account for the asymmetry\(^1\).

To obtain an approximate position of the dynamical center of the explosion one would need to trace back the expansion of the SNR to the time of the explosion from the SNR expanding filaments. Unlike in SNe II, neither in SN 1572 nor in any other SN Ia has the derivation been possible thus far, due to the faintness of the filaments. This measurement remains an interesting long–term project to be undertaken with the use of large telescopes. In this work, arguments based on what is found in SNe II together with the E–W geometrical asymmetry of this SNIa are used to establish the area of the search.

\(^1\) Decourchelle, A. et al. XMM-Newton observation of the Tycho supernova remnant *Astron & Astrophys.* 365, L218–L224 (2001).
Supplementary Discussion

Further discussion on red giants and main sequence stars

Red giants In the red-giant companion case, the envelope is loosely bound gravitationally, and upon collision with the SN Ia ejecta it should be either completely stripped or just a small fraction of it remain bound to the core$^{1,2}$. If the full envelope were lost, the remaining He core would appear as a hot He pre-white dwarf, not as a red giant. Our survey would have revealed the presence of hot helium stars resulting from complete stripping of the envelope of a red giant because they are brighter than the other stars that we do observe. If a minor fraction of the envelope of the red giant were retained instead, the H-burning shell would remain active and the residual envelope would expand to red-giant size. In the case of Tycho A, whose envelope is $\sim 2.6 \, M_\odot$, nothing similar to the star that we are now seeing could ever be what remains after the supernova impact. Tycho A and the other red giants are in any case ruled out on the basis of their incompatible distance with SN 1572.

Main sequence stars We should emphasize that there exists, beyond differences in the post-explosion evolution calculations, unanimous agreement that the companion object, if it were a main-sequence star, should exhibit an odd combination of stellar parameters ($\log g$ and $T_{\text{eff}}$) for its mass and that it should move fast$^{1,3,4,5}$. That is not found in the observed sample of main-sequence stars. Apart from Tycho B (see Figure 3), there are six main-sequence stars in Table 1. One of them (Tycho J) is a spectroscopic binary made of two main-sequence stars with similar spectral types (G8/K0-K3). Its radial velocity fits the derived distance, and no such system is likely to be the surviving companion of any SN Ia. As stated above, all main-sequence stars of spectral type earlier than K6 were detected to the distance of the remnant. The total mass available for transfer in main-sequence stars of type later than K6 ($M \lesssim 0.6 \, M_\odot$) excludes these stars as viable candidates to SN Ia companions.
1 Canal, R., Méndez, J. & Ruiz-Lapuente, P. Identification of the companion stars of Type Ia supernovae. *Astrophys. J.* **550**, L53–L56 (2001)

2 Livne, E., Tuchman, Y. & Wheeler, J.C. Explosion of a supernova with a red giant companion. *Astrophys. J.* **399**, 665–671 (1992)

3 Ruiz-Lapuente, P., Comeron, F., Smartt, S., Kurucz, R., Méndez, J., Canal, R., Filippenko, A., Chornock, R. Search for the companions of Galactic SNe Ia, in *From Twilight to Highlight: the Physics of Supernovae*, 140, ed. W. Hillebrandt & B. Leibundgut (Berlin: Springer-Verlag) (2003).

4 Marietta, E., Burrows, A. & Fryxell, B. Type Ia supernova explosions in binary systems: the impact on the secondary star and its consequences. *Astrophys. J. Suppl.* **128**, 615–650 (2000).

5 Podsiadlowski, P. On the evolution and appearance of a surviving companion after a Type Ia supernova explosion, astro-ph/0303660 (2003).
Supplementary Figure 1. Spectra of Tycho G showing it to be a subgiant not belonging to the halo population. (Right panel) Several fits to Fe and Ni lines in Tycho G for solar abundances (bold) and abundances $[\text{Fe/H}] = -0.5$ (dashed line) and $[\text{Fe/H}] = -1$ (dotted line). This star does not belong to the halo population: it shows solar metallicities in Fe and Ni. The observed spectra were obtained with ISIS at the WHT. (Left panel) A low-resolution spectrum over a wide wavelength range was obtained with LRIS at the Keck
Observatory (second from top) and it is compared with template model spectra of the same spectral class and various metallicities. It has also been used to determine the atmospheric parameters (see main text). Very high and low metallicities are excluded. The spectrum of Tycho G confirms that it is a subgiant star.
Supplementary Note 2

Tycho Brahe SN as a U Sco system

The evolutionary path that gave rise to SN 1572 could be similar to that leading to the recurrent nova U Scorpii pointed out as a candidate to SN Ia progenitor. The companion candidate is now a mildy evolved star within the solar mass range. The excess velocity implies an orbit of 6 days before the explosion. Starting from a white dwarf with a mass \( \sim 0.8 \, M_\odot \) plus a somewhat evolved companion of \( \sim 2.0-2.5 \, M_\odot \) filling its Roche lobe, and with a period of 12 days, it would have ended up as a white dwarf at the Chandrasekhar mass (\( \sim 1.4 \, M_\odot \)) plus a companion of roughly 1 \( M_\odot \), the period then being \( \sim 6 \) days (orbital velocity \( \sim 90 \) km/s). The effective radius of the Roche lobe of the companion just before explosion would have been \( \sim 7 \, R_\odot \). Now the radius of the companion has to be less than three times the solar radius given the effective temperature and luminosity of the star. The smaller current radius would result from the opposite effects of mass stripping and shock heating by the supernova impact, plus subsequent fast cooling of the outer layers up to the present time.