The binary progenitor of Tycho Brahe's 1572 supernova

Pilar Ruiz-Lapuente[1,2], Fernando Comeron[3], Javier Méndez[1,4], Ramon Canal[1], Stephen J. Smartt[5], Alexei V. Filippenko[6], Robert L. Kurucz[7], Ryan Chornock[6], Ryan J. Foley[6], Vallery Stanishev[8] & Rodrigo Ibata[9]

[1]*Department of Astronomy, University of Barcelona, Marti i Franques 1, E-08028 Barcelona, Spain*
[2]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany*
[3]*European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching, Germany*
[4]*Isaac Newton Group, PO Box 321, Santa Cruz de La Palma, Tenerife, Canary Islands, E-38780 Spain*
[5]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[6]*Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, California 94720-3411, USA*
[7]*Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA*
[8]*Department of Physics, Stockholm University, AlbaNova University Center, SE-108 91 Stockholm, Sweden*
[9]*Observatoire de Strasbourg, 11, rue de l'Université, F-67000 Strasbourg, France*

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 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 $b = +1.4°$, 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 $-30\,\mathrm{km\,s^{-1}}$ at 3 kpc. The predictions of how the companion star would look after the impact of the supernova ejecta, 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 supernova 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, like 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 $300\,\mathrm{km\,s^{-1}}$, 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

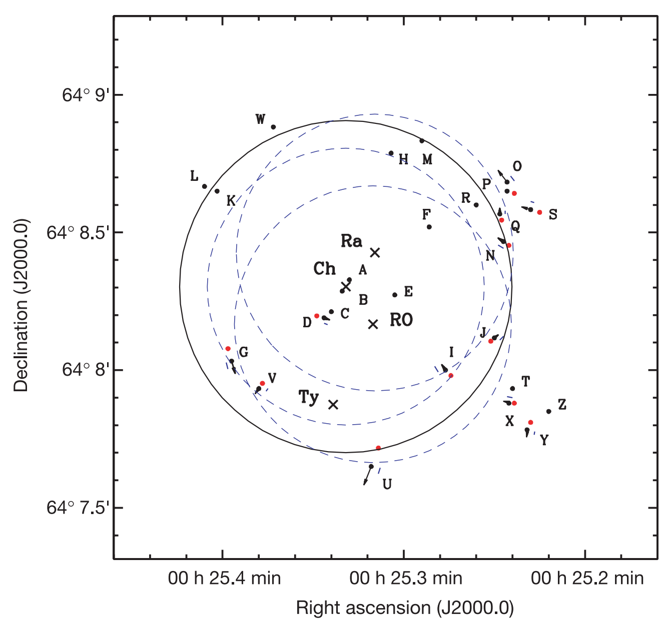

Figure 1 Positions and proper motions of stars. Positions are compared with three centres: the Chandra (Ch) and ROSAT (RO) geometrical centres of the X-ray emission, and that of the radio emission (Ra). Dashed lines indicate circles of 0.5 arcmin around those centres. The supernova position reconstructed from Tycho Brahe's measurements (Ty) is also shown, though merely for its historical interest[21]. 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[8,22,23]. 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[23] (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 centre is found in the most symmetric cases[24]. 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 indicating 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, as both stars U and O are at much shorter distances (see Supplementary Methods).

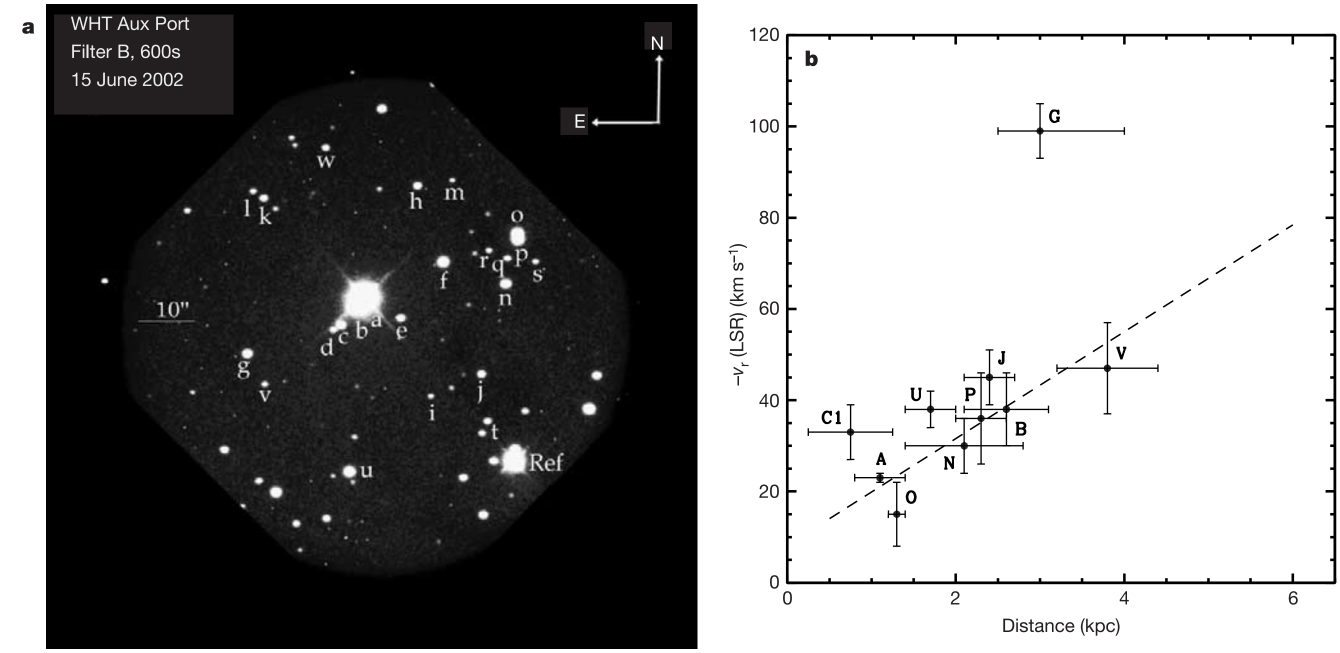

Figure 2 The SN 1572 field and radial velocity of the stars. **a**, Image from the Auxiliary Port at the William Herschel Telescope. It confirms the relative emptiness of the field. The search area (see also Fig. 1 bold circle) covers a radius of 0.65 arcmin around RA = 00 h 25 min 19.9 s, dec. = 64° 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 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.)

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 $V = 22$ (Figs 1 and 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[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[12]. Among systems containing a main-sequence star, recurrent novae have been pointed out as possible progenitors[13]. Stripping of mass from the impact of the ejecta on this type of companion is also expected[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[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

Table 1 **Characteristics of the supernova companion candidates**

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

Supernova companion candidates within the search radius and limiting magnitude. Angular distances θ 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[26], with the Uppsala Synthetic Spectrum Package[27]. This determines the atmospheric parameters effective temperature T_{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_{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.

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[16], after dereddening by $E(B - V) \approx 0.6$ mag, gives a best fit for an effective temperature $T_{eff} = 5{,}750$ 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, and 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 ($M \approx 1M_\odot$) and thus the radius, for the range of surface gravities above, should be $R \approx 1$–$3R_\odot$, 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[9,10,14,15].

Stars at distances $d \approx 2$–4 kpc, in that direction, are moving at average radial velocity[17] $v_r \approx -20$ to $-40\,\mathrm{km\,s^{-1}}$ (in the Local Standard of Rest), with a $\sim 20\,\mathrm{km\,s^{-1}}$ velocity dispersion[18,19]. Tycho G moves at $-108 \pm 6\,\mathrm{km\,s^{-1}}$ (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 3σ 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 Hubble Space Telescope WFPC2 images[20] whether Tycho G has a high tangential velocity

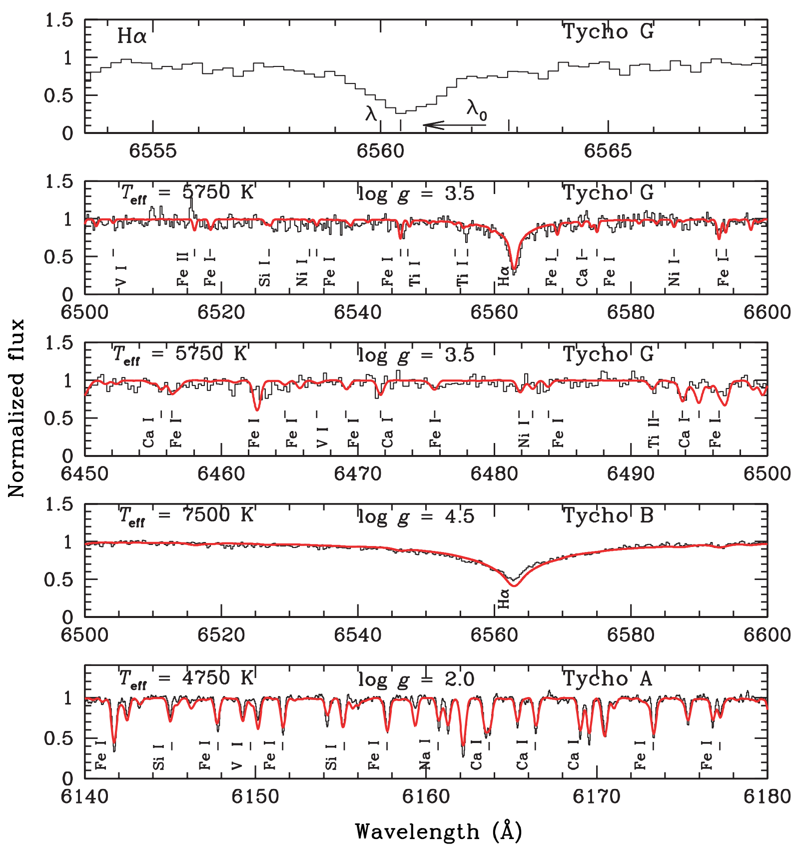

Figure 3 Model fits to observed spectra. Model atmosphere parameters are those listed in Table 1, and chemical abundances are solar. They are shown here for our candidate star for the companion of SN 1572 (Tycho G) and the red giant (Tycho A) and main-sequence star (Tycho B) nearest to the distance of SN 1572 and to the SNR 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 white dwarf. 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).

as well (see Supplementary Table 2 and Supplementary Methods). Tycho G has significant proper motion toward lower Galactic latitude: $\mu_b = -6.11 \pm 1.34\,\mathrm{mas\,yr^{-1}}$ (the proper motion along longitude is small, $\mu_l = -2.6 \pm 1.34\,\mathrm{mas\,yr^{-1}}$). The proper motion in Galactic latitude implies that this star is an outlier in proper motion as well, with a derived tangential velocity of $94 \pm 27\,\mathrm{km\,s^{-1}}$ (a $24\,\mathrm{km\,s^{-1}}$ systematic error was added, resulting from a $1.7\,\mathrm{mas\,yr^{1}}$ 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 $136\,\mathrm{km\,s^{-1}}$, which is a factor of over 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 $[\mathrm{M/H}] > -0.5$ (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 affected 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. □

Received 14 June; accepted 8 September 2004; doi:10.1038/nature03006.

1. Branch, D., Livio, M., Yungelson, L. R., Boffi, F. & Baron, E. In search of the progenitors of Type Ia Supernovae. *Publ. Astron. Soc. Pacif.* **107,** 1019–1029 (1995).
2. Ruiz-Lapuente, P., Canal, R. & Burkert, A. in *Thermonuclear Supernovae* (eds Ruiz-Lapuente, P., Canal, R. & Isern, J.) 205–230 (Kluwer Academic, Dordrecht, 1997).
3. Livio, M. in *Type Ia Supernovae: Theory and Cosmology* (eds Niemeyer, J. C. & Truran, J. W.) 33–48 (Cambridge Univ. Press, Cambridge, 2000).
4. Brahe, T. Astronomiae Instauratae Progymnasmata. In *Opera Omnia* Vol. 2 (ed. Dreyer, I. L. E.) 307 (Swets & Zeitlinger, Amsterdam, 1972) (1603).
5. Baade, W. B Cassiopeiae as a supernova of Type I. *Astrophys. J.* **102,** 309–317 (1945).
6. Baldwin, J. E. & Edge, D. O. Radio emission from the remnants of the supernovae of 1572 and 1604. *Observatory* **77,** 139–143 (1957).
7. Hughes, J. P. *et al.* ASCA observations of the Large Magellanic Cloud supernova remnant sample: Typing supernovae from their remnants. *Astrophys. J.* **444,** L81–L84 (1995).
8. Canal, R., Méndez, J. & Ruiz-Lapuente, P. Identification of the companion stars of Type Ia supernovae. *Astrophys. J.* **550,** L53–L56 (2001).
9. Ruiz-Lapuente, P. Tycho Brahe's supernova: light from centuries past. *Astrophys. J.* **612,** 357–363 (2004).
10. Ruiz-Lapuente, P. *et al.* in *From Twilight to Highlight: the Physics of Supernovae* (eds Hillebrandt, W. & Leibundgut, B.) 140–147 (Springer, Berlin, 2003).
11. Hachisu, I., Kato, M. & Nomoto, K. A new model for progenitor systems of Type Ia supernovae. *Astrophys. J.* **470,** L97–L100 (1996).
12. Li, X.-D. & van den Heuvel, E. P. J. Evolution of white dwarf binaries: supersoft X-ray sources and progenitors of type Ia supernovae. *Astron. Astrophys.* **322,** L9–L12 (1997).
13. Livio, M. & Truran, J. W. Type I supernovae and accretion-induced collapses from cataclysmic variables? *Astrophys. J.* **389,** 695–703 (1992).
14. 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).
15. Podsiadlowski, P. On the evolution and appearance of a surviving companion after a Type Ia supernova explosion. Preprint at ⟨http://arxiv.org/astro-ph/0303660⟩ (2003).
16. Lejeune, Th., Cuisinier, F. & Buser, R. A standard stellar library for evolutionary synthesis. *Astron. Astrophys. Suppl. Ser.* **125,** 229–246 (1997).
17. Brand, J. & Blitz, L. The velocity field of the outer Galaxy. *Astron. Astrophys.* **275,** 67–90 (1993).
18. Binney, J. & Merrifield, M. *Galactic Astronomy* (Princeton Univ. Press, Princeton, 1998).
19. Dehnen, W. & Binney, J. Local stellar kinematics from *Hipparcos* data. *Mon. Not. R. Astron. Soc.* **298,** 387–394 (1998).
20. Ruiz-Lapuente, P. Probing the nature of Type Ia SNa through HST astrometry. ⟨http://archive.stsci.edu/cgi-bin/proposal_search?mission = hst&id = 9729⟩ (2003).
21. Ruiz-Lapuente, P. in *Proc. Conf. Astronomy as a Model for the Sciences in Early Modern Times, Munich, 21–23 March 2003* (eds Fritscher, B. & Kühne, A.) (Erwin Rauner, Augsberg, in the press).
22. Hughes, J. P. The expansion of the X-ray remnant of Tycho's supernova (SN 1572). *Astrophys. J.* **545,** L53–L56 (2000).
23. Decourchelle, A. *et al.* XMM-Newton observation of the Tycho supernova remnant. *Astron. Astrophys.* **365,** L218–L224 (2001).
24. ⟨http://cxc.harvard.edu/cda/⟩
25. Anders, E. & Grevesse, N. Abundances of the elements—meteoritic and solar. *Geochim. Cosmochim. Acta* **53,** 197–214 (1989).
26. Kurucz, R. L. ATLAS9 Stellar Atmospheres Programs, Grids of Model Atmospheres and Line Data [CD-ROM]. (Smithsonian Astrophysical Observatory, Cambridge, MA, 1993).
27. Gustaffson, B., Bell, R. A., Eriksson, K. & Nordlund, Å. A grid of model atmospheres for metal-deficient giant stars. *Astron. Astrophys.* **42,** 407–432 (1975).
28. Schmidt-Kaler, Th. in *Landolt-Börnstein, New Ser. VI*, Vol. 2b (ed. Hellwege, K.-H.) 1–34 (Springer, Berlin, 1982).

Supplementary Information accompanies the paper on **www.nature.com/nature**.

Acknowledgements P.R.L. thanks C. Ruiz Ogara for giving her the spirit to complete this survey. We thank the support staff at the European Northern Observatory at La Palma for their assistance throughout this project, as well as the support staff at the W. M. Keck Observatory and NASA/ESA Hubble Space Telescope. We express our special gratitude to C. Abia, F. Figueras, C. Guirao, R. Mignani and J. Torra for diverse consultations. This work has been supported by DURSI, DGYCIT (to P.R.L., J.M. and R.C.), PPARC (to J.M. and S.J.S.) and by NSF (to A.V.F., R.C., R.J.F. and R.L.K.).

Competing interests statement The authors declare that they have no competing financial interests.

Correspondence and requests should be addressed to P.R.L. (pilar@am.ub.es).

Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity

Benjamin Levrard[1]*, François Forget[2], Franck Montmessin[3] & Jacques Laskar[1]

[1] *Astronomie et Systèmes Dynamiques, IMC-CNRS UMR8028, 77 Avenue Denfert-Rochereau, 75014 Paris, France*
[2] *Laboratoire de Météorologie Dynamique, Université Paris VI, 4 Place Jussieu, 75005 Paris, France*
[3] *Space Science Division MS 245-3, NASA/Ames Research Center, Moffett Field, California 94035, USA*

* Present address: Laboratoire de Planétologie et télédétection, UMR 5570, UCBL-ENS Lyon, 43 boulevard du 11 novembre 1918, 69622 Villeurbanne, France

Observations from the gamma-ray spectrometer instrument suite on the Mars Odyssey spacecraft have been interpreted as indicating the presence of vast reservoirs of near-surface ice in high latitudes of both martian hemispheres[1–5]. Ice concentrations are estimated to range from 70 per cent at 60° latitude to 100 per cent near the poles, possibly overlain by a few centimetres of ice-free material in most places[4]. This result is supported by morphological evidence of metres-thick layered deposits that are rich in water-ice[6–9] and periglacial-like features[10,11] found only at high latitudes. Diffusive exchange of water between the pore space of the regolith and the atmosphere has been proposed to explain this distribution[12], but such a degree of concentration is