The Search for the Companion Star of Tycho Brahe's 1572 Supernova

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In recent years, type Ia supernovae (SNe Ia) have been used successfully as cosmological probes of the Universe (Riess et al., 1998; Perlmutter et al., 1999). However, the nature of their progenitors has remained somewhat of a mystery. It is widely accepted that they represent the disruption of a degenerate object, but there are also numerous progenitor models (see for instance Ruiz-Lapuente, Canal, Isern, 1997a, for a review), but most of these have serious theoretical/observational problems or do not appear to produce sufficient numbers to explain the observed frequency of SNe Ia in our Galaxy (~3×10^{-3} yr^{-1}; Cappellaro & Turatto, 1997).

The Thermonuclear Runaway

Hoyle and Fowler (1960) described how a white dwarf, a common end-point in the evolution of low- and intermediate-mass stars, could become a powerful fusion bomb if its interior temperature rose from about 2×10^8 to 5×10^8 K. They anticipated that this type of explosion could well correspond to the class of objects identified by Minkowski (1941), called supernovae of type I and much later renamed type Ia. These supernovae are characterised by their spectral signatures and are the brightest observable stellar explosions.

But, how can such high temperatures (>10^8 K) be attained in the usually cold degenerate cores of white dwarfs? A natural way to heat white dwarfs up is by the accretion of material from a stellar companion. If the white dwarf grows in mass by taking material from a donor star, its central density and temperature rise, and it can achieve the critical condition near 1.4 solar masses, the so-called Chandrasekhar mass. The binary path is found to be the easiest physical way to give rise to bare white dwarfs exploding in large enough numbers to account for those supernovae. The single-star models were both physically and statistically unsuccessful. Recently, new momentum has been given to the study of possible evolutionary paths to explosion. Observational efforts with specific goals have been set up to clarify the issue by contrasting the models with empirical evidence.

Progenitor Models of Type Ia SNe

The progenitor models can roughly be divided into three classes: double-degenerate (DD) models, sub-Chandrasekhar models and single-degenerate (SD) Chandrasekhar models.

The DD alternative involves the progressive approach of two white dwarfs orbiting around the centre of mass of the system while they emit gravitational wave radiation (the material accreted by the white dwarf is neither H nor He but C+O from a disrupted CO white-dwarf companion) (Iben & Tutukov, 1984; Webbink, 1984). The less massive white dwarf is disrupted in the process, forming a torus of material around the most massive one. The accretion of this mass by the surviving white dwarf could cause its explosion if the combined mass is in excess of the Chandrasekhar mass (~1.4 solar masses). The lack of detection of any surviving companion could eventually confirm that it is destroyed in the course of the binary evolution, as expected in the merging of CO white dwarfs. Some objections have been raised, however: fine tuning in the accretion process might be required to avoid the burning of C into Ne and Mg, which would lead to a collapse event (i.e. undergoes accretion-induced collapse; AIC) instead of an thermonuclear explosion. There may be a small parameter range where AIC can be avoided, but it is unlikely to account for more than a small number of SNe Ia. This model nevertheless has the advantage of being in good agreement with the SN rate in our Galaxy (Nelemans et al., 2001).

A sub-Chandrasekhar-mass white dwarf could produce a SN Ia if helium is ignited violently in a shell surrounding the CO core and triggered a detonation wave that propagates inward and ignites the CO core (Woosley & Weaver, 1994; Livne & Arnett, 1995). Although they might not respond to the common type Ia phenomenon, they could correspond to very dim ones. A mixture of almost standard Chandrasekhar explosions with some very faint "peculiar" sub-Chandrasekhar explosions could exist. A few extremely faint type Ia explosions have been identified, in any case: The last supernova of type Ia that exploded in the Andromeda galaxy, in 1885, was of such a type. On the other hand, the evolutionary path toward explosion will not be directly reflected in the spectrum of the exploded white dwarf itself.

The arguably most favoured class of models at the present time involves single-degenerate scenarios, where the white dwarf accretes from a non-degenerate companion star (Whelan & Iben, 1973; Nomoto, 1982). In these models, the companion star can be a giant, a subgiant, a He star, or a main-sequence star, ie. it may either be a hydrogen-rich star or a helium star. One of the major problems with these models is that it is generally difficult to increase the mass of a white dwarf by accretion due to the occurrence of nova explosions and/or helium flashes (Nomoto, 1982) which may eject most of the accreted mass. There is a narrow parameter range where a white dwarf can accrete hydrogen-rich material and burn it in a stable manner. Burning of the accreted H into He and of the He into C can lead to the growth in mass and increase of the central temperature of the star, which would finally explode. Low accretion rates favours a much less violent explosion: A nova, which differs from a supernova in that the white dwarf remains intact, and there is opportunity for further recurrent outbursts. Whereas a nova is a skin-depth explosion, a type Ia supernova affects the whole star. A number of tests have been undertaken to reveal whether such a picture involving a H- or He-donor companion is correct (Ruiz-Lapuente, 1997b).

One promising channel that has been identified in recent years relates them to supersoft X-ray sources (Li & van den Heuvel, 1997). In this channel, the companion star is a somewhat evolved main-sequence star or subgiant of 2–3 solar masses, transferring mass on a thermal timescale to a white dwarf. As an example, calculations made by Podsiadlowski (2003) show that an initial system consisting of a 2.1 solar masses somewhat evolved main-sequence star and a 0.8 solar masses white dwarf can make the white dwarf grows very effectively. When it reaches the Chandrasekhar mass, it has parameters very similar to U Scorpii, a supersoft binary and recurrent nova where the white dwarf is already close to the Chandrasekhar mass and therefore one of the best SN Ia progenitors currently known (Thoroughgood et al., 2001).

While U Scorpii provides an excellent candidate for a SN Ia, consistent with theoretical expectations, it would be even better to have a more direct observational test for progenitor models (Ruiz-Lapuente, 1997b), in particular since it is quite possible, perhaps even likely, that there is more than one channel that leads to a SN Ia. Such direct tests could involve the detection of hydrogen or helium in the ejecta or the supernova environment, which could come from the outer layers of the exploding object, circumstellar material that was ejected from the progenitor system (e.g. Cumming et al., 1996), or matter that was stripped from the

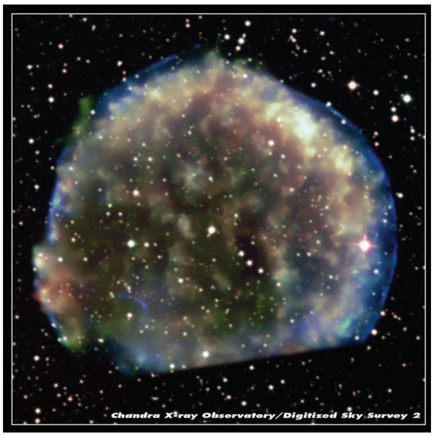


Figure 1. Chandra image of Tycho SNR. The colours in the Chandra X-Ray image of the hot bubble show different X-ray energies, with red, green, and blue representing low, medium, and high energies, respectively. (The image is cut off at the bottom because the southernmost region of the remnant fell outside the field of view of the Chandra camera). The bright star in the centre of the remnant is the same bright star in the centre of Figure 2 (star labelled 'Tycho A'). Credit: Chandra X-Ray Observatory/DSS2.

secondary by the supernova interaction and was mixed into the ejecta. A particularly conclusive test would be the detection of a companion star that has survived the supernova explosion in the supernova remnant. At present the detection of a surviving companion would only be feasible in our Galaxy. The supernova of the millennium, the Lupus supernova (also designated SN 1006 after the year of its appearance) was a supernova of this type. The supernova discovered by Tycho Brahe, SN 1572, was also of this type. Both are the only unambiguous type Ia supernovae observed in our Galaxy during the last thousand years.

Observable Consequences on the Companion Star

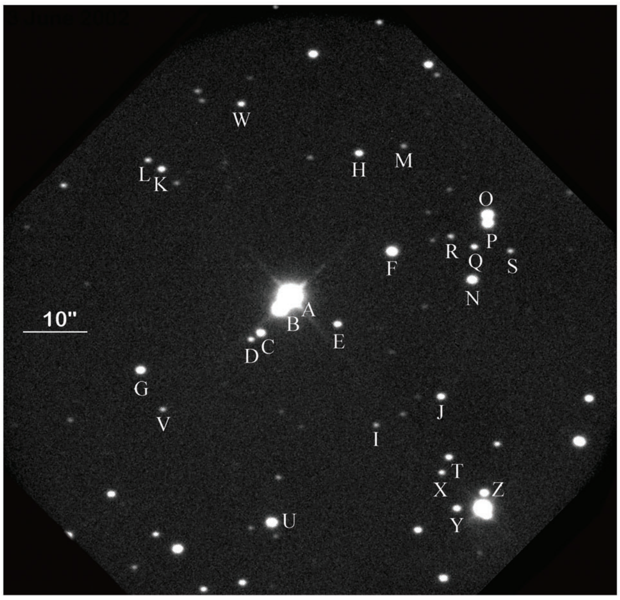
The predictions of how the companion star would look after the impact of the supernova ejecta, if there is any companion, were investigated by Canal, Méndez and Ruiz-Lapuente (2001), depending on the type of star it actually is. Among other features, the surviving companion star should have a peculiar velocity with respect to the average motion of the other stars at the same location in the Galaxy —mainly due to disruption of the binary— detectable through proper-motion and 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 the 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.

The Search for the Companion Star of SN 1572

Tycho Brahe's supernova (SN 1572) is one of the only two supernovae observed in our Galaxy that are thought to have been of type Ia as revealed by the light curve (Ruiz-Lapuente, 2004), radio emission (Baldwin et al., 1957) and X-ray spectra (Hughes et al., 1995).

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 km s^{-1} at 3 kpc. 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, showing an unusual motion in comparison to the stars at the same location, having stellar parameters consistent with being struck by the supernova explosion and lying near the remnant centre.

The distance to SN 1572 inferred from the expansion of the radio shell and by other methods lies around 3 kpc. Such a distance, and the light-curve shape



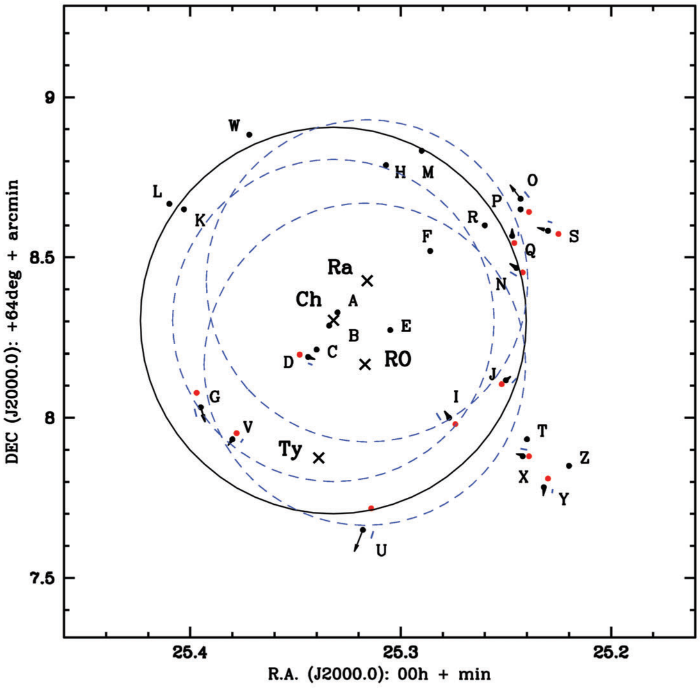


Figure 2 (left). B-band image of the centre of Tycho SNR from the Auxiliary Port camera at the William Herschel Telescope. The emptiness of the field is remarkable. We carried out repeated photometric and spectroscopic observations of the included stars in the surveyed area (see solid circle in Figure 3) at various epochs to check for variability and exclude binarity.

Figure 3 (right). 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 and the solid line is a circle with a radius of 0.65 arcmin around the Chandra centre. The supernova position reconstructed from Tycho Brahe's measurements (Ty) is also shown, though merely for its historical interest. The proper motions of the stars measured from HST WFPC2 images are represented by arrows, their lengths indicating the total displacements from 1572 to 2004. Error bars are shown by parallel segments. Red circles are the extrapolated positions of the stars back to 1572.

of SN 1572, are consistent with it being a normal type Ia supernova in luminosity, like those commonly found in cosmological searches (Ruiz-Lapuente, 2004).

Given the age of Tycho SNR and the lower limit to its distance (2.83±0.79 kpc), any possible companion, even if it moved at a speed of 300 km s^{-1}, could not be farther than 0.15 arcmin from its position at the time of the explosion. However, the search radius significantly expands owing to the uncertainty in the derived centre of the SNR. The radius of the remnant is 4.325±0.025 arcmin (Ruiz-Lapuente, 2004) and the SNR is quite spherically symmetric (see Figure 1). Nevertheless, 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. Such asymmetry amounts to a 14% offset along the east–west axis. Evidence that the ejecta encountered a dense H-cloud at the eastern edge giving rise to brighter emission and lower ejecta velocity, while finding a lower-density medium in the western rim, might account for the asymmetry (Decourchelle et al., 2001). In SNRs from core-collapse supernovae (type II), up to a 15% discrepancy between the location of the compact object and the geometric centre is found in the most symmetric cases.

On the basis of the above considerations we decided to cover 15% of the innermost radius (0.65 arcmin) centred on RA=00 25 19.9, Dec=64 08 18.2 (J2000), the Chandra Observatory coordinates for the geometrical centre of the X-ray emission of the SNR (Figures 2 and 3). And as deep as V=22 so sampling main-sequence with spectral types earlier than K6 (for later types the total mass available for transfer excludes them as viable candidates to type Ia SN companions), subgiant and red giant candidates at the distance of the remnant (Canal, Méndez, Ruiz-Lapuente, 2001). For a description of our survey strategy see Ruiz-Lapuente et al. (2003a).

We obtained spectra of most of the stars in the surveyed area using Keck I, II+ESI, LRIS, WHT+UES, ISIS and NOT+ALFOSC, and photometric data using the INT+PFC, WFC and WHT+Aux Port Camera. All but one of the observed stars 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 are the most favourable cases (Hachisu et al., 1996). Red-giants have envelopes loosely bound gravitationally, and upon collision with the SN ejecta it should be either completely stripped or just a small fraction of it remains bound to the core. In the former case, the remaining

He core would appear as a hot He pre-white dwarf, not as a red giant. In the latter case, the H-burning shell would remain active and the residual envelope would expand to red-giant size. None of the detected red-giant stars lie in one of these possibilities and they are all at distances incompatible with that of SN 1572.

Main-sequence stars are also viable companions of type Ia supernovae. Close binaries with 2 to 3.5 solar masses main-sequence or subgiant companions have indeed been suggested as one class of systems able to produce type Ia supernovae (Li et al., 1997). Among systems containing a main-sequence star, recurrent novae have been pointed out as possible progenitors (Livio & Truran, 1992). Stripping of mass from the impact of the ejecta on this type of companion is also expected and as a consequence the companion star increases its volume and luminosity, to later return to the equilibrium values of a star with the new (decreased) mass (Canal et al., 2001; Marietta et al., 2000; Podsiadlowski, 2003). Main-sequence companions should experience the highest increase in peculiar velocity (peculiar velocities up to 200 to 300 km s^{-1} after the explosion) as the orbital separation of the binary system is shorter than in other possible progenitor models. However, the detected main-sequence stars in the sample have low peculiar velocities, the surface abundances are compatible with solar values and no odd combinations of log g and T_{eff} are found.

The Case of Tycho G

Tycho G is a subgiant G2IV star located at 0.49 arcmin from the Chandra centre of Tycho SNR. From low resolution spectroscopy, and after dereddening by $E(B–V)$=0.60±0.05 mag, we derive a temperature of T_{eff}=5750 K, a surface gravity log g=4.0–3.0, and solar metallicity from high-resolution spectroscopy. For the spectral type found and being a slightly evolved star (surface gravity not much below the main-sequence value), the mass should be about solar and thus the radius, for the range of surface gravities above,

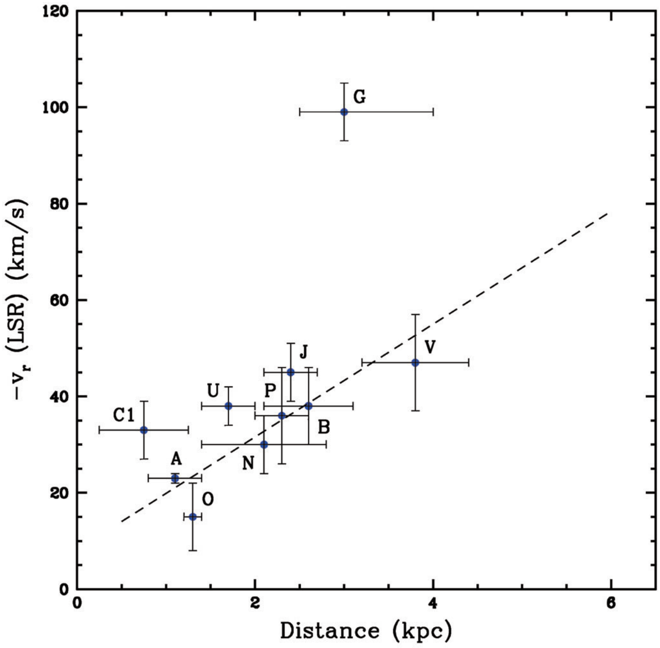


Figure 4. Radial velocity in the Local Standard of Rest (LSR), versus distance for the subsample of stars closer than 6.5 kpc. The dashed line shows the approximate relationship for the stars in the direction of Tycho given by the expression v_r=–v_{solar} cos(l–l_{solar})+$A\,r$ sin(2l), where l and l_{solar} are the respective Galactic longitudes of Tycho SNR and the solar apex, v_{solar} is the Sun's velocity in the LSR, A is the Oort's constant and r is the distance in kpc. We include two field stars (stars Tycho O and U) that are slightly away from the search area but at distances in the range 2–4 kpc.

should be $R\approx$1–3 solar radii, which translates via our photometric data (Tycho G's apparent V magnitude is 18.71±0.04) into a distance $d\approx$2.5–4.0 kpc.

Tycho G could have been a main-sequence star or a subgiant before the explosion. Main-sequence stars no longer look like ordinary main-sequence stars after the explosion of the supernova, but subgiants with envelopes expanded. Subgiants remain subgiants of lower surface gravity (Marietta et al., 2000; Podsiadlowski, 2003).

Stars at distances $d\approx$2.0–4.0 kpc in the direction of Tycho SNR move at average radial velocity $v_r\approx$–20 to –40 km s^{-1} (in the Local Standard of Rest) with a ~20 km s^{-1} velocity dispersion (Binney & Merrifield, 1998; Dehnen & Binney, 1998). Tycho G moves at –108±6 km s^{-1} (heliocentric) in the radial direction. In contrast, all other stars with distances compatible with that of SN 1572 have radial velocitites within the velocity dispersion as compared with the average of all stars at the same location in the Galaxy (see Figure 4).

From detailed proper motion measurements on Hubble Space Telescope WFPC2 images (Ruiz-Lapuente et al., 2003b) it is found that Tycho G has tangential velocitites μ_b=–6.11±1.34 mas yr^{-1} and μ_l= –2.60±1.34 mas yr^{-1} resulting in a total tangential velocity of 94±27 km s^{-1} (a 24 km s^{-1} systematic error was added due to uncertainty in the reference frame solution of the images). This proper motion programme continues in HST Cycle 13 where measurements with smaller error bars will be obtained using both WFPC2 and ACS. The other stars of our sample do not show such coincidence in distance and high tangential velocity. Putting together radial and tangential velocities, we derive a value of 136 km s^{-1} for the modulus of the velocity vector of Tycho G, being a factor of 3 larger than the mean velocity value at 3 kpc.

This derived velocity lies in the range of expected peculiar velocities of the companion star from the disruption of a white dwarf plus subgiant/main-sequence system. The system would have resembled the recurrent nova U Scorpii, ie. a system made of a white dwarf close to the Chandrasekhar mass

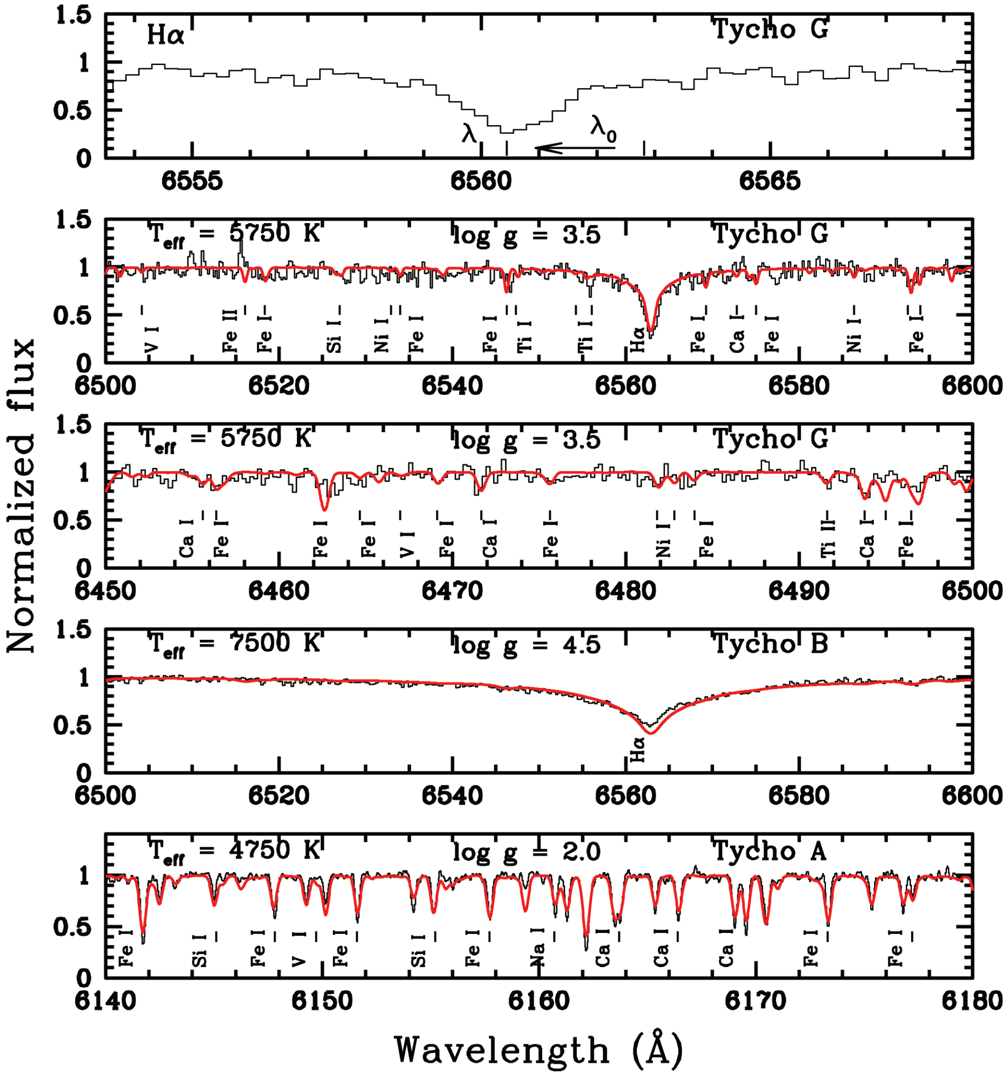


Figure 5. Model fits to observed spectra of the subgiant star Tycho G, the red giant star Tycho A and the main-sequence star Tycho B. Identification of the most significant metal lines are given. We have not detected significant spectroscopic anomalies, either here or in the whole sample, and most spectra are well reproduced assuming solar abundances. Thin lines correspond to the observations and thicker lines to the synthetic spectra. Spectra were obtained at the 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 mas should be 3 solar masses approximately. Tycho A is ruled out as the companion star of SN 1572 on the basis of its short distance: 1.1±0.3 kpc. All the other red giants are located well beyond Tycho´s remnant, and therefore are also ruled out. The A8/A9 star Tycho B (second panel from bottom) has 1.5 solar masses, 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 second and third spectra from the top show computed spectra compared with observed spectra for Tycho G. 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.

(initial mass of the white dwarf 0.8 solar masses) plus a companion of roughly a solar mass (initial mass of the evolved companion 2.0–2.5 solar masses filling its Roche lobe) at the moment of the explosion. The excess velocity corresponds to a period of about 2–7 days (a period of 6 days correspond to an orbital velocity of 90 km s^{-1} approximately). The effective radius of the Roche lobe of the companion just before the explosion would have been 7 solar radii.Given the effective temperature and luminosity of Tycho G, the radius is less than 3 times the solar radius. This smaller radius would be a consequence of mass stripping and shock heating by the supernova impact, plus subsequent fast cooling of the outer layers up to the present time.

Such a high velocity, however, could be explained if Tycho G belongs to the Galactic halo population. The lower limit to the metallicity obtained from the spectral fits [M/H]>–0.5, however, excludes this possibility (see Figures 5 and 6). Spectra taken at five different epochs also exclude Tycho G is a single-lined spectroscopic binary.

Conclusions

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. One of the stars, Tycho G of our sample, show a high peculiar velocity (both radial and tangential velocities), lies within the distance range for the explosion of SN 1572, and its type, G2IV, fits the post-explosion profile of a type Ia supernova companion whose position in the Hertzsprung-Russell diagram is untypical for a standard subgiant.

If Tycho G is the companion star of SN 1572, its overall characteristics imply that the supernova explosion affected the companion mainly through the kinematics. Therefore, a star very similar to the our Sun but of a slightly more evolved type would have been the mass donor that triggered the explosion of type Ia SN 1572, connecting the supernova explosion to the family of cataclysmic variables.

The results of this research, led by Pilar Ruiz-Lapuente of the University of Barcelona, was published in the October 28 issue of *Nature*. The co-authors are Fernando Comeron (ESO), Javier Méndez (University of Barcelona and ING), Ramón Canal (University of Barcelona), Stephen Smartt (IoA, Cambridge), Alex Filippenko (University of California, Berkeley), Robert Kurucz (Harvard-Smithsonian Centre for Astrophysics), Ryan Chornock and Ryan Foley (University of California, Berkeley), Vallery Stanishev (Stockholm University), and Rodrigo Ibata (Observatory of Strasbourg). ¤

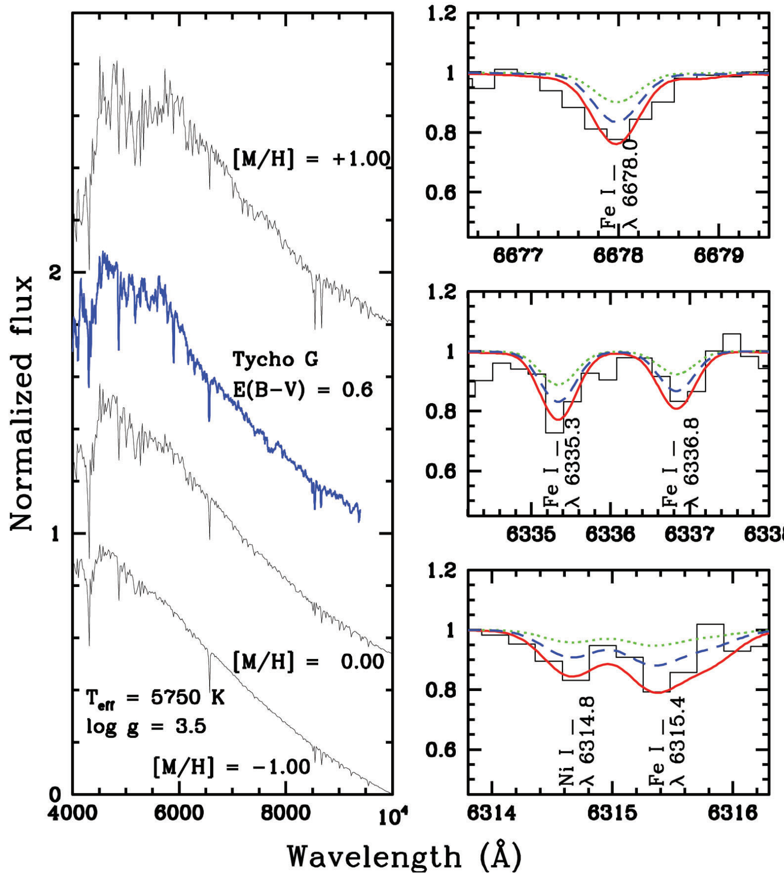


Figure 6. Left: A low-resolution spectrum over a wide wavelength range was obtained with LRIS at the Keck Observatory (second from top) and it is compared with template model spectra of the same spectral class and various metallicities. Right: Several fits to Fe and Ni lines in Tycho G for solar abundances (bold line), [Fe/H]=–0.5 (dashed line) and [Fe/H]=–1 (dotted line). The high content of nickel and iron in the gas of Tycho G clearly identifies it as a star born in the Galactic Plane. The data was obtained with ISIS at the WHT.

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