

The progenitor of Tycho Brahe's 1572 supernova

Pilar Ruiz-Lapuente^{1,2}, Fernando Comeron³, Javier Méndez^{1,4}, Ramon Canal¹, Stephen J. Smartt⁵, Alexei V. Filippenko⁶, Robert L. Kurucz⁷, Ryan Chornock⁶, Ryan J. Foley⁶, Vallery Stanishev⁸, & Rodrigo Ibata⁹

¹ Department of Astronomy, University of Barcelona, Martí 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, P.O. 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, CA 94720-3411 USA

⁷ Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 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

In contrast with the far-reaching implications of Type Ia supernovae (SNe Ia) as cosmological probes, 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. Unless the companion star is another WD (in which case it should be destroyed by the mass-transfer process itself), it should survive and show distinguishing properties. We saw in Tycho’s supernova (the SN Ia observed by Tycho Brahe and other astronomers in 1572)^{1,2}, a unique opportunity to observationally address the identification of the surviving companion of SNe Ia. Here we show that a survey of the central region of its remnant, around the position of the explosion, excludes red giants as the mass donor of the exploding WD. We report that 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 appears to be the companion of the supernova.

Tycho Brahe’s supernova (i.e., SN 1572) is one of the only two supernovae observed in our Galaxy that is 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^{1,2,3,4}.

The field which contained Tycho’s supernova, relatively devoid of background stars, is favorable for searching for any surviving companion. With a Galactic latitude $b = +1.4^\circ$, Tycho’s SN 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^{5,6,7}. 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 SN 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. 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 impacted by the SN explosion. It should also lie near the remnant center (i.e., 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 SN Ia in luminosity, as those commonly found in cosmological searches⁹. Given the age of the 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 due to the uncertainty in the derived centre of the SNR (see Figure 1).

We have analyzed 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, 2 and 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 SNe Ia. Masses in the range 0.9–1.5 M_{\odot} would be the most favourable cases¹¹. 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 (Figure 3), but it is closer than SN 1572 and shows no peculiarities in velocity, spectral type, or metallicity. *Main-sequence stars* are also viable SN Ia companions. 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 SNe Ia¹². Among systems containing a main-sequence star, recurrent novae have been pointed out as possible progenitors¹³. 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 explosion are shortest), but the measured values of 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 Figure 1, Table 1 and Supplementary Table 3) are found at wider separations from the geometrical centre, but they have radial velocities (v_r) 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 that fits well the expectations for distance, reddening, and velocity. Comparison of the Tycho G spectrum covering a wide wavelength range ($\lambda\lambda 3180\text{--}9400 \text{ \AA}$) with templates¹⁶, after dereddening by

$E(B - V) \approx 0.6$ mag, gives a best fit for an effective temperature $T_{eff} = 5750$ 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 Figure 3, Supplementary Figure 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 $R \approx 1\text{--}3 R_{\odot}$, which translates (via our photometric data) into a distance $d \approx 2.5\text{--}4.0$ 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 SN Ia explosion (and they might resemble subgiants, their envelopes having expanded after the SN impact), subgiants would remain subgiants of lower surface gravity^{9,10,14,15}.

Stars at distances $d \approx 2\text{--}4$ kpc, in that direction, are moving at average radial velocity¹⁷ $v_r \approx -20$ to -40 km s⁻¹ (in the Local Standard of Rest), with a ~ 20 km s⁻¹ velocity dispersion^{18,19}. Tycho G moves at -108 ± 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 (i.e., 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 *HST* WFPC2 images²⁰ 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: $\mu_b = -6.11 \pm 1.34$ mas yr⁻¹ (the proper motion along longitude is small, $\mu_l = -2.6 \pm 1.34$ 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 ± 27 km s⁻¹ (a 24 km s⁻¹ systematic error was added, resulting from a 1.7 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 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 $2.6''$ North of the current location of this star based on 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 SN Ia 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 $[M/H] > -0.5$ (see Figure 3 and see Supplementary Figure 1), which excludes its belonging to the Galactic halo population as an alternative explanation of its high velocity. Spectra taken at five different epochs exclude as well its being a single-lined spectroscopic binary. If our candidate is the companion star, its overall characteristics imply that the SN explosion would affect the companion mainly through the kinematics. Our search for the binary companion of Tycho’s supernova has excluded giant stars. It also has 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 which triggered the explosion of SN 1572. That would connect the explosion to the family of cataclysmic variables.

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

FIGURE CAPTIONS

Figure 1 Stars positions and proper motions. 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 $0.5'$ around those centers. The SN position reconstructed from Tycho Brahe’s measurements (Ty) is also shown, though merely for its historical interest²¹. 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 $0.56'$ displacement along the E–W 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 rim²³ (Supplementary Note 1). Such asymmetry amounts to a 14% offset along the E–W axis. In SNRs from core-collapse SNe (SNe II), up to a 15% discrepancy between the location of the compact object and the geometric center is found in the most symmetric cases²⁴. Based on 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 1572 and present. Error bars are shown by parallel segments. Red circles are the extrapolated positions of the stars back to 1572 AD. 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. Image from the Auxiliary (Upper) Port at the William Herschel Telescope. It confirms the relative emptiness of the field. The search area (see also Figure 1 bold circle) covers a radius of 0.65 arcmin around R.A. = 00 25 19.9 Dec = 64 08 18.2 (J2000) (the *Chandra* geometrical center 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 $A_V = 1.7\text{--}2.0$ mag toward the candidate stars (see Supplementary Table 3), our search limit down to an apparent visual magnitude $V = 22$ imply 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.

(Lower) Radial velocity (in the LSR) *vs* 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 constant¹⁸. 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.

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 and the red giant and main-sequence star nearest to the distance of SN 1572. Identifications of the most significant metal lines are given. We have not detected significant spectroscopic anomalies, neither here nor in the whole sample, and most spectra are well reproduced assuming solar abundances²⁸. 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 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 SN Ia 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 middle panels show computed spectra compared with observed spectra obtained at the WHT with ISIS. The upper panel shows the observed spectrum near $H\alpha$. 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 Figure 1).

TABLE CAPTION

Table 1. Supernova companion candidates within the search radius and limiting magnitude. Angular distances θ are from the Chandra X-ray geometrical center, located at R.A.= 00 25 19.9 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 Kurucz²⁵, with the Uppsala Synthetic Spectrum Package²⁶. This determines the atmospheric parameters effective temperature and surface gravity. Intrinsic colors and absolute visual magnitudes are deduced from the relationships between spectral type and color and between spectral type and absolute magnitude for the different luminosity classes²⁷. 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. 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'' apart. Modeling 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 $\mu_l = -3.23$, $\mu_b = -0.58$ [± 0.66] (same error in both coordinates, units in mas yr^{-1}) for star D, $\mu_l = -2.60$, $\mu_b = -6.11$ [± 1.34] for star G, $\mu_l = 3.23$, $\mu_b = 1.45$ [± 1.15] for star N, and $\mu_l = 1.61$, $\mu_b = -2.85$ [± 0.78] for star V.

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

Star	θ (arcsec)	Spec. type & 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	$3.0^{+0.5}_{-0.5}$	$0.60^{+0.09}_{-0.09}$	> 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	$4.5^{+0.5}_{-0.5}$	$0.60^{+0.10}_{-0.10}$	$3.8^{+0.6}_{-0.6}$

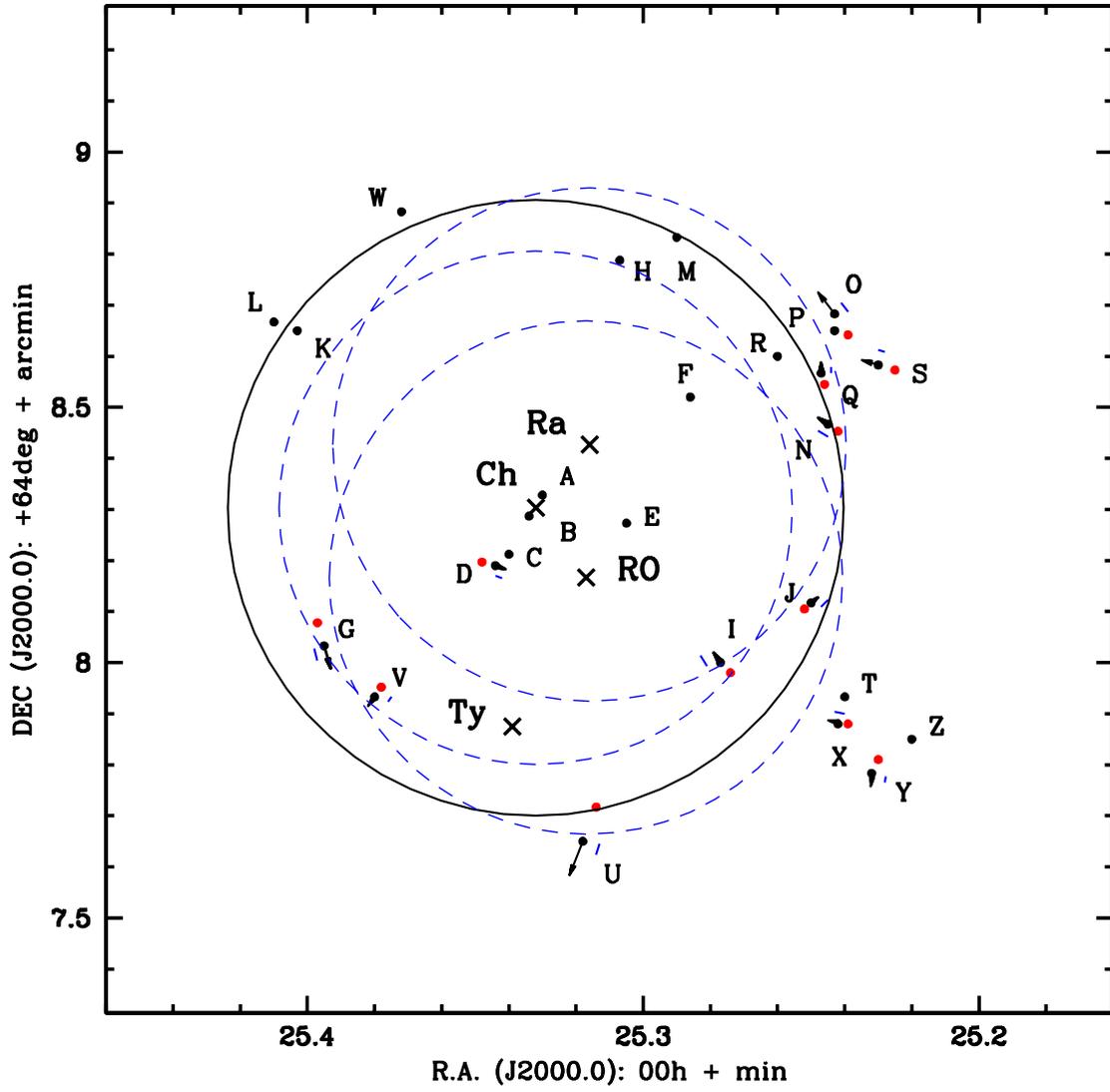


Fig. 1.—

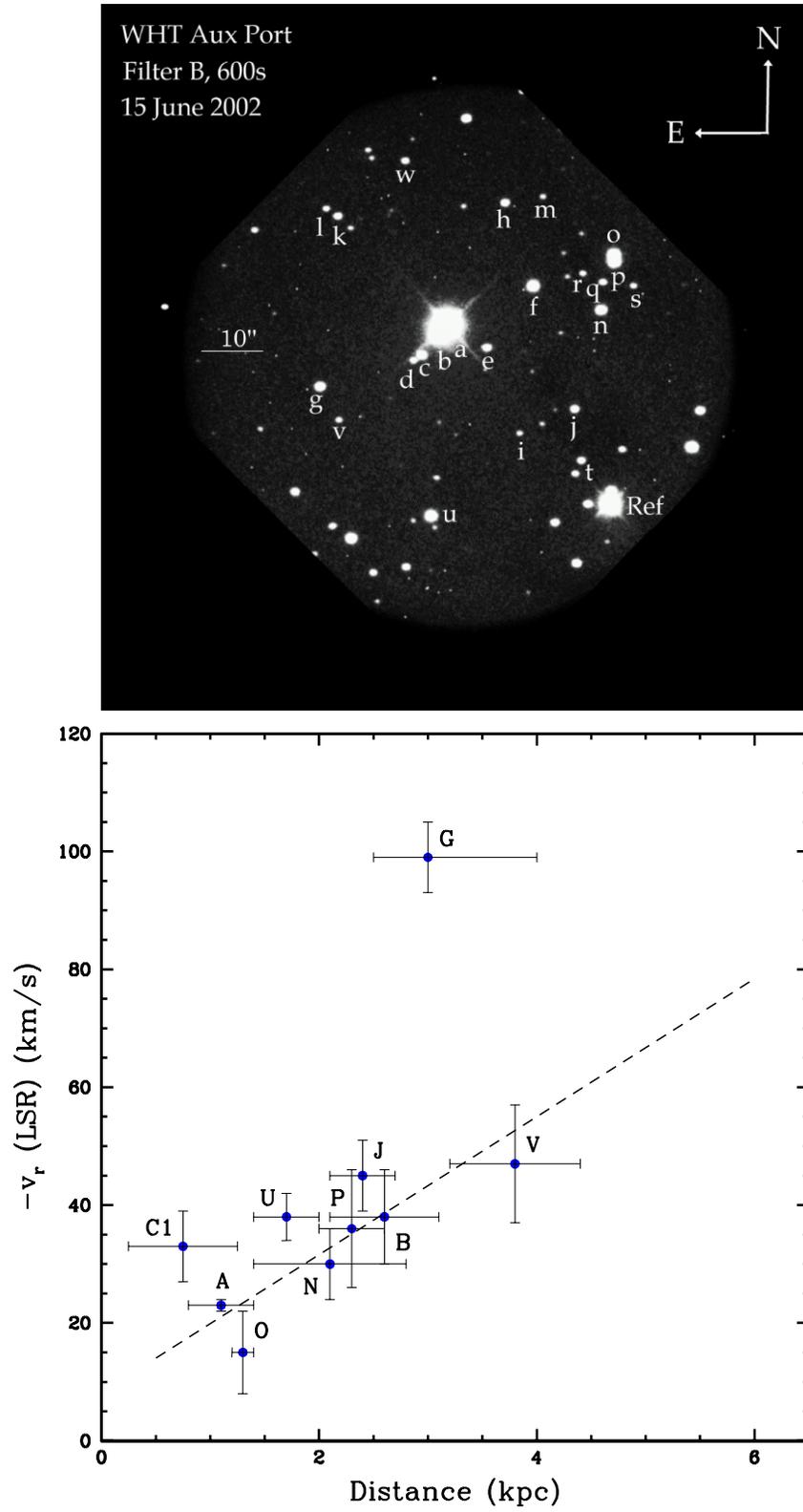


Fig. 2.—

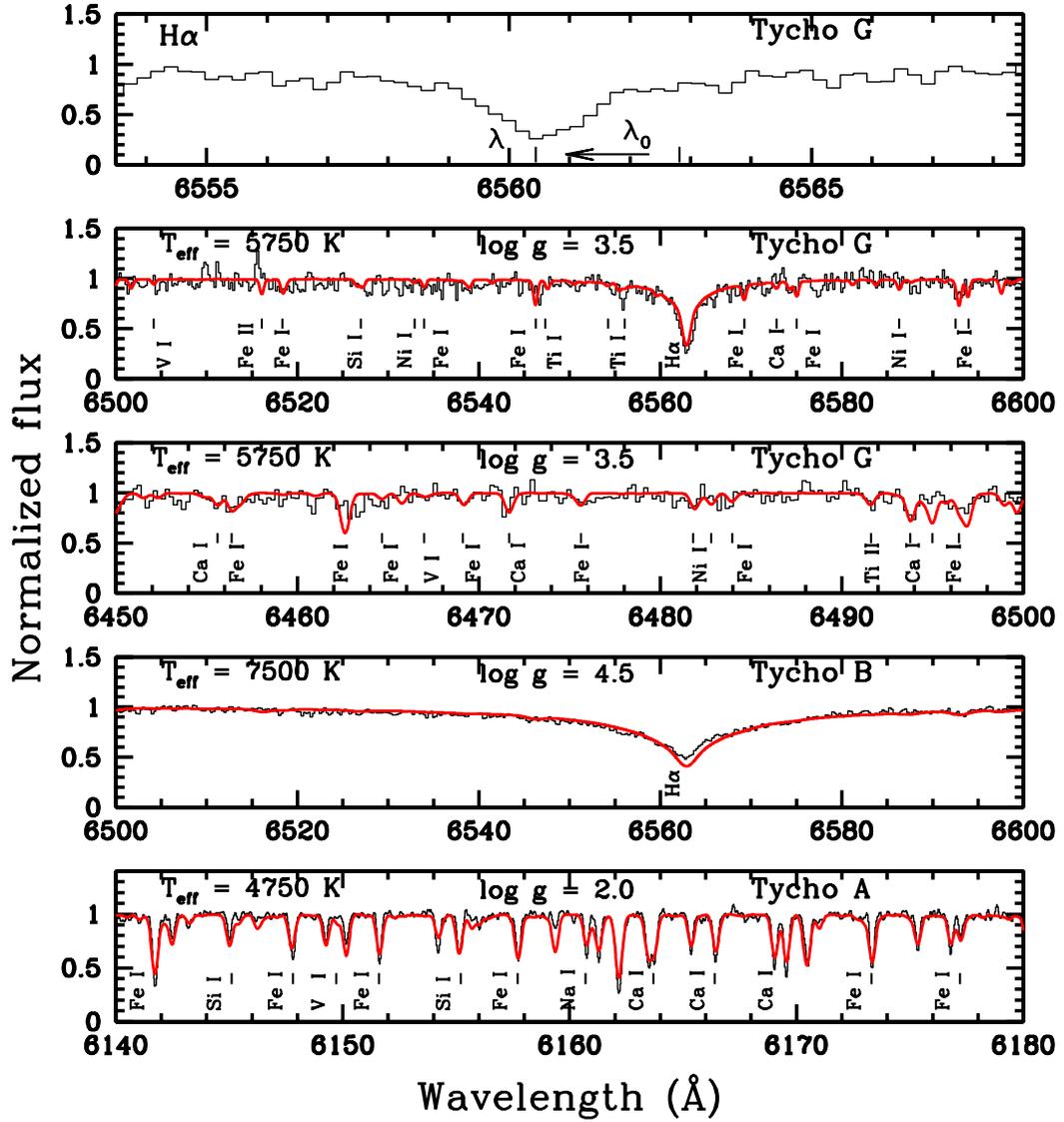
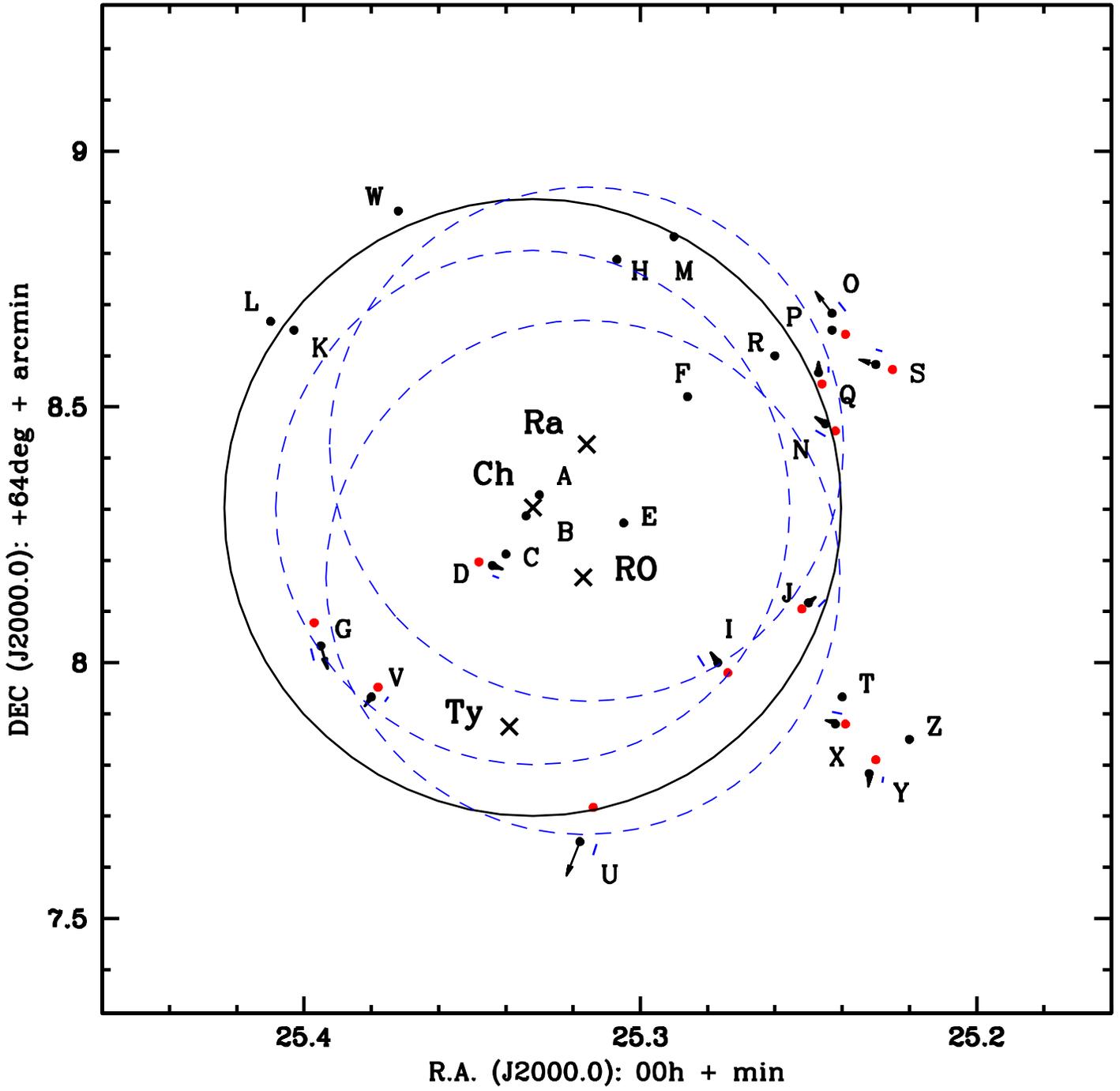


Fig. 3.—



WHT Aux Port
Filter B, 600s
15 June 2002

