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Tycho-B: an unlikely companion for SN 1572*

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ABSTRACT

If some or all Type Ia SNe arise from accretion onto a massive WD from a companion, then the companion will remain in some form after the SN explosion. Tycho-B is an unusual, relatively hot star along the line of sight to Tycho's SNR – conclusively shown to be a Type Ia – and has been suggested as such a companion. If the interior of Tycho's SNR contains unshocked Fe, and if Tycho-B is either within the SNR shell or in the background, then one might hope to see evidence of this in the UV spectrum. Such is the case for SN 1006, where spectra of the background Schweizer–Middleditch star, as well as two AGNs, show broad absorption lines of Fe II. To test this idea, we have used STIS on *HST* to obtain a UV spectrum of Tycho-B. The observed spectrum, however, shows no evidence of Fe II absorption. Furthermore, a luminosity distance estimate using UV and optical spectra of Tycho-B suggests that the star is consistent with a foreground interloper. We conclude either that Tycho-B is nearer than Tycho's SNR, or that all of the Fe in the interior of Tycho's SNR is more highly ionized.

Key words: binaries: symbiotic – supernovae: individual: SN1572 – ISM: supernova remnants.

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are of great interest to astronomy, not only as end-points of stellar evolution, but also as one of the most powerful cosmological distance probes. It is therefore unfortunate that the progenitor evolution is not understood. While there is consensus that the SN Ia phenomenon is powered by the thermonuclear explosion of a relatively massive ($>1\,M_\odot$) CO white dwarf, it is unclear how this thermonuclear run-away is triggered or how such a massive object is created. One possibility – known as the singly-degenerate (SD) scenario – is that the white dwarf grows to a mass of 1.38 through accretion from a companion star and then self-ignites when the centre reaches $\rho > 10^9$ g cm^{-3}. While the massive white dwarf explodes, the companion star will survive in most cases (e.g. Marietta, Burrows & Fryxell 2000; Pakmor et al. 2008; Pan, Ricker & Taam 2013; Shappee, Kochanek & Stanek 2013).

The most popular alternative is the doubly degenerate (DD) scenario, the merger of two degenerate objects (white dwarfs or stellar cores), leading to ignition (Iben & Tutukov 1984; Webbink 1984; Livio & Riess 2003; van Kerkwijk, Chang & Justham 2010; Kashi & Soker 2011). Another possibility starts by a detonation wave running around the outer accreted helium layer of the white dwarf (see e.g. Fink et al. 2010; Shen & Moore 2014). This sends shocks that coalesce at the centre and raise the densities and temperatures resulting in a runaway thermonuclear detonation.

The accretion (SD) scenario makes a clear prediction that would not occur in alternatives: the donor companion star survives the explosion. This has motivated a number of searches for such survivors in various SN Ia remnants. (e.g. Ruiz-Lapuente 2004; González Hernández et al. 2009; Kerzendorf et al. 2009, 2014; Schaefer & Pagnotta 2012). Here we focus on the efforts involving the remnant of Tycho's supernova (SN 1572).

Tycho is a young SNR whose X-ray emission is dominated by emission from a reverse shock that is still propagating into ejecta from the explosion. Inside the reverse shock, the remaining ejecta are expected to freely expand, cold, and not highly ionized. In the remnant of SN 1006, also widely believed to have been an SN Ia (but without a light-echo confirmation), the cold ejecta have been observed spectroscopically through absorption from Fe (and Si) using light from a background sub-dwarf B star (now known as the

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SM star, Schweizer & Middleditch 1980) and two fainter AGN (Wu et al. 1983, 1993; Winkler et al. 2005), all of which provide 'core samples' through the SN 1006 shell.

A number of searches for surviving companions in Tycho's SNR have been carried out, and several candidates have been suggested (see Ruiz-Lapuente et al. 2004; González Hernández et al. 2009; Kerzendorf et al. 2009, 2013; Bedin et al. 2014).

There are three promising progenitor candidates: Tycho-G (see Ruiz-Lapuente et al. 2004), Tycho-E (Ihara et al. 2007), and Tycho-B (Kerzendorf et al. 2013). While Tycho-E and Tycho-G have some unusual characteristics compared to field stars (see Ruiz-Lapuente et al. 2004 and Ihara et al. 2007, respectively), these sources can either be explained by normal stellar evolution (Tycho-G; Kerzendorf et al. 2013) or are too far from the remnant to be a plausible candidate (Tycho-E, at distance ~10 kpc; Kerzendorf et al. 2013).

The most unusual star near the centre of the Tycho remnant (see Fig. 1) is Tycho-B, first suggested as a candidate by Kerzendorf et al. (2013). With an effective surface temperature $T_{\rm eff} \approx 10\,000$ K, surface gravity $\log g \approx 4.0$, and metallicity [Fe/H] ≈ -1, it is a young metal-poor star within the disc of the Galaxy and exhibits enhancements in carbon and oxygen. It also exhibits a relatively high rotational velocity ($v_{\rm rot} \approx 170$km s^{-1}) which is, however, not unusual for A-stars. Thompson & Gould (2012) have suggested that Tycho-B, as surviving companion, might be explained if SN 1572 resulted from a quadruple-star system.

Tycho-B is bright enough in the UV that if it lies either within or beyond Tycho's SNR, and if Tycho's SNR still contains significant amounts of Fe^{+}, then one might hope to find broad absorption lines of Fe II in its spectrum, as is the case for the objects behind SN 1006. To test this possibility, we have obtained UV spectra of Tycho-B with *HST*/STIS (GO 13432). Of the stars near the (projected) centre of Tycho*'s* SNR. Tycho-B is the only one bright enough in the UV to permit such an experiment, the results of which we report here. We describe the observations and data reduction in Section 2, followed by presentation of our detailed analysis in Section 3. We then discuss our key results in Section 4 and summarize our results in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

We observed Tycho-B in a single two-orbit visit on 2014 September 30 using the STIS low-resolution grating (G230L) and the NUV-MAMA detector with the 52 × 0.5 arcsec slit, which provided wavelength coverage from 1570 to 3180 Å with a resolution of about 3 Å, appropriate for searches for broad absorption lines. Photometry of earlier UV images (from *HST* Prop ID 6435) shows that Tycho-B has *U*-band (F336W) magnitude 16.78, bright enough that a relatively short *HST*/STIS observation should yield high enough signal to noise to detect broad Fe II absorption features if these are present. We eliminated most contamination from the nearby (2.7 arcsec) and brighter (U=15.96) star Tycho-A by rotating the slit perpendicular to a line connecting Tycho-A and Tycho-B. Two spectra were obtained with exposure times of 2630 and 3238 s. (The exposures were different in length because a portion of the first orbit was taken up with acquisition, using Tycho-A).

The data used in our analysis were processed using version 3.4.1 of the STIS pipeline (in 2017 September). The average of the extracted x1d spectra, along with a model with the stellar parameters from Kerzendorf et al. (2013), can be seen in Fig. 2. For comparison we also show the UV spectrum of the Schweizer and Middleditch (1980) star that is behind the Type Ia remnant SN 1006, which shows prominent broad Fe II absorption lines – features that are completely missing from Tycho-B's spectrum.

3 ANALYSIS

In order to quantify our basic observational result that the spectrum does not contain absorption lines similar to those seen in SN 1006. we have carried out a detailed Bayesian analysis of the spectrum, in an attempt to answer two key questions: (1) How stringent are the limits on possible broad Fe II absorption? (2) What is the allowed distance range for Tycho-B, and how does this compare with the distance of *Tycho*'s SNR?

3.1 Models

For modelling the spectrum, we generated synthetic spectra using the STARKIT framework. Within STARKIT, we used the PHOENIX grid of synthetic spectra (Husser et al. 2013), which spans 2300 K $< T_{\rm eff} <$ 12000 K, $0.0 < \log g < 4.5$, and $-1.5 <$ [M/H] < 1. Starting from a model intrinsic spectrum, we then (a) convolve for a given $v_{\rm rot}$ (assuming a limb darkening of 0.6), (b) shift the spectrum for a given $v_{\rm rad}$, (c) apply extinction parametrized with A_V (assuming $R_V = 3.1$) according to Cardelli, Clayton & Mathis (1989), (d) convolve with the appropriate instrumental profile (in our case $\Delta\lambda = 3$ Å), and (e) interpolate on the wavelength grid to match the observed data. The flux of this synthetic model is then scaled to match the observed spectra of Tycho-B. This results in the stellar model $M_{\rm Tycho\text{-}B}(T_{\rm eff}, \log g, {\rm [Fe/H]}, v_{\rm rot}, v_{\rm rad}, A_V) \mapsto F_\lambda(\lambda)$.

We assume that the most prominent absorption features from the remnant would be the Fe II lines at 2383 and 2600 Å, respectively. We model the amplitude of these two features independently, but assume that both have the same velocity broadening profile. Our model sees Tycho-B being within the remnant (no red-shifted component). The spectrum does not show any obvious absorption features and thus a pure in-remnant model is enough to quantify how much absorption might be possible without being immediately visible. The model is then $M_{\rm absorption}(A_{2383}, A_{2600}, \sigma, v_{\rm remnant}) \mapsto {\rm Transmission}(\lambda)$.

3.2 Priors

We choose the uncertainties given in Kerzendorf et al. (2013) as priors for our model of Tycho-B: $T_{\rm eff} = 10\,000^{+200}_{-400}$ K, [M/H] $= -1 \pm 0.4$, $v_{\rm rot} = 171^{+16}_{-33}$ km s^{-1}, and $v_{\rm rad} = -51 \pm 2$ km s^{-1}. We use the maps provided by Green et al. (2015) to obtain the extinction between 1–5kpc and obtain a uniform prior for A_V= 2.2–3.1. We assume a uniform prior for the amplitude for any absorption feature in our models of 0–1. We require the velocity shift imposed by the remnant's expansion of 0–6000km s^{-1} (using the expansion velocities by Sato and Hughes 2017 as a guide). We assume a uniform prior for the broadening of 500–6000 km s^{-1} (using the uncertainties in the expansion velocities as a lower limit and the expansion velocities as an upper limit by Sato and Hughes 2017).

The determination of the surface gravity is of crucial importance for the distance estimate. The stellar features in the current STIS spectrum (mainly the Mg II doublet at 2800 Å) are only very mildly sensitive to the surface gravity. Kerzendorf et al. (2013) provide an LRIS spectrum (3200–5600Å) covering the log$g$ sensitive Balmer break region. This previous analysis – using a predecessor of STARKIT – provided only a rough estimate for the uncertainty. We have redetermined the log g posterior probability using the setup described in this work for the spectral fit (see Fig. 3). We note that the large absorption feature missing in our models near 4400 Å is a diffuse

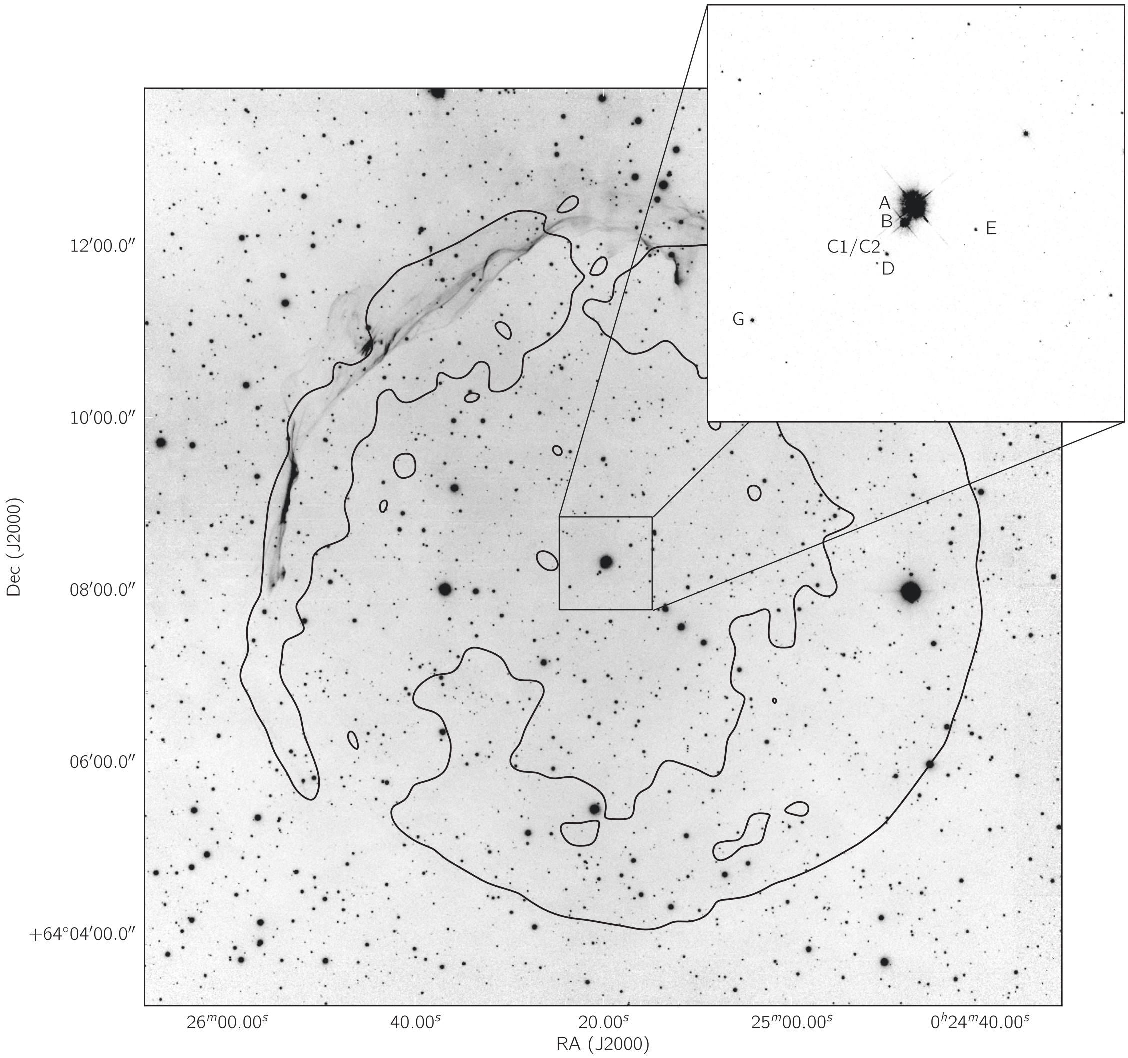


Figure 1. Hα imagery from the 3.5 m WIYN telescope at KPNO, obtained in 2009 September (Putko, Winkler & Blair 2015) of the remnant of SN 1572 with contours from *Chandra* X-ray image (4.1–6.1 keV). The detailed inset shows an *HST WFPC2* image, using the F555W filter (Ruiz-Lapuente et al. 2004), of the centre showing the candidate star Tycho-B and the other candidates near the centre.

interstellar band. The fit gives an extremely tight 68 per cent quantile ($\log g = 4.23 \pm 0.01$) which we will use as a $\log g$ prior for our Tycho-B fit. We note that the uncertainty is certainly underdetermined, and we take this into account in the discussion.

3.3 Parameter inference

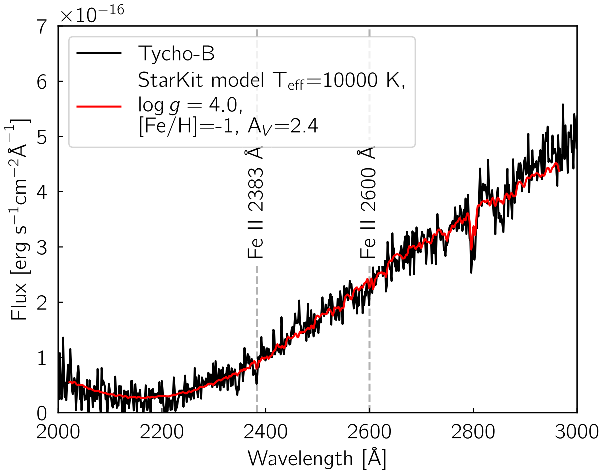
We use the MULTINEST algorithm to infer the parameters (using the implementation available at https://github.com/kbarbary/nestle). The stopping criterion for such an algorithm is a comparison with an estimate of unaccounted evidence Z_{est} when compared to the currently calculated evidence Z_i for iteration i. We choose the default value of $\log(Z_i + Z_{\mathrm{est}}) - \log Z_i < 0.5$ for this criterion.

We explore the parameter space for our models to match the data in three stages. We first explore the Kerzendorf et al. (2013) LRIS spectrum to get a prior for $\log g$ (see Fig. 3). We then explore the stellar parameters (including the luminosity distance) using the flux calibrated STIS spectrum presented in this work and assuming the given priors (see Fig. 4). Finally, we fit our model with the potential remnant absorption features and stellar parameters appropriate to Tycho-B. We show this posterior probability marginalized over the stellar parameters in Fig. 5. For both models (with and without remnant absorption features), we show a selection of fits from the 68 per cent quantile in Fig. 6

4 DISCUSSION

In our detailed analysis, we try to quantify how much absorption is still possible in the Tycho-B spectrum given no absorption being immediately visible in the spectrum (see Fig. 2). Fig. 5 shows very low possible EW for the features (both of them likely upper limits) with $0.7^{+1.03}_{-0.52}$ Å and $2.19^{+0.88}_{-0.93}$Å for the $\lambda\lambda$2382 Å and 2600 Å lines, respectively. The EW for these lines measured in the SM star behind SN 1006 is much larger: 15.4 Å and 14.8 Å for the $\lambda\lambda$2382 Å and 2600 Å lines, respectively. Tycho-B could be within or behind the remnant, but only if the column density of Fe II is extremely low.

One explanation might be that the density of cool iron is much lower than expected, resulting in no absorption features (despite similar features in the SN Ia remnant SN 1006, Winkler et al. 2005). In this regard, it should be pointed out that our detailed understand-



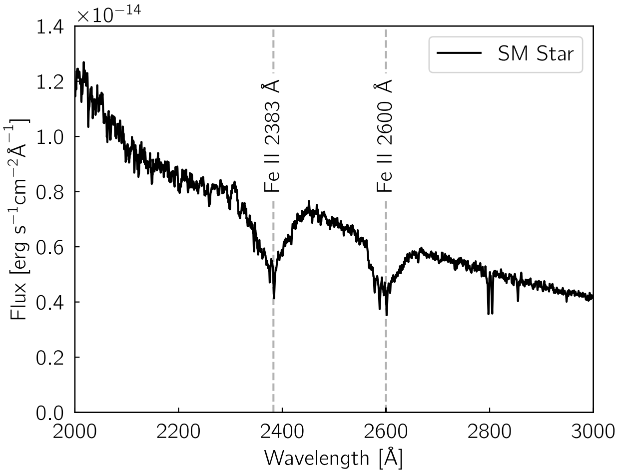


Figure 2. *Upper Panel:* The average of the observed STIS spectra of Tycho-B overplotted with a stellar model given the parameters in Kerzendorf et al. (2013) *Lower Panel:* A Faint Object Spectrograph (*HST*) spectrum of the Schweizer Middleditch star from (Wu et al. 1993) showing the strong Fe absorption features from the foreground remnant SN 1006.

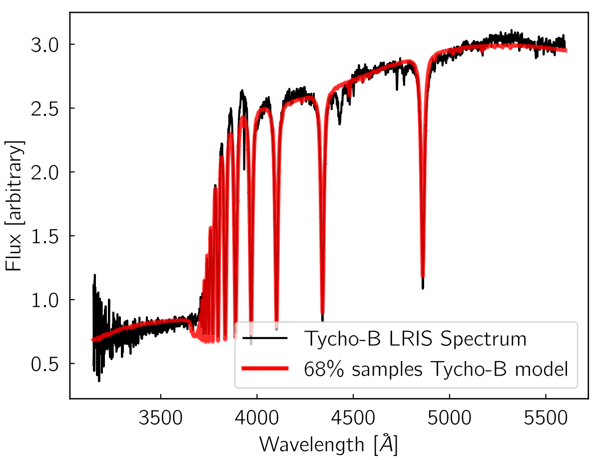


Figure 3. *Tycho*-B LRIS spectrum (Kerzendorf et al. 2013) with a STARKIT fit used to constrain log g.

ing of Fe in SN 1006 is not as precise as one might like. The total amount of Fe II (and Fe III) in SN 1006 is considerably less than expected for an SN Ia explosion, 0.2–0.3 $M_\odot$. Hamilton, Fesen, and Blair (2007) report a value of 0.044 $M_\odot$ with a 3σ limit of 0.16 $M_\odot$. Hamilton and Fesen (1988) interpreted this as due to photon ionization from the reverse shock in SN 1006. (They also predicted that the lines in Tycho's SNR should be similar to those in SN 1006.) Subsequently, primarily as a result of observations obtained of Fe III lines in the FUV and an analysis of lines of Si II, Hamilton et al. (2007) concluded that Fe is not very highly ionized in the interior of SN 1006.

To assess these possibilities, we next discuss independent distance measurements for both the *Tycho* SNR and Tycho-B.

4.1 Distance to the Tycho SNR

The distance to the Tycho SNR is itself quite uncertain. Reconstructions of the light curve based on 16th century records from Tycho and others have long provided evidence that it was a Type Ia event, with apparent visual magnitude at maximum of -4.0 ± 0.3 (Baade 1945; Ruiz-Lapuente 2004). Krause et al. (2008) observed the light-echo spectrum from SN 1572 (over four centuries later) and showed conclusively that it had been a Type Ia event. Comparison with several template SN Ia spectra shows that it was a normal Type Ia, and correcting for extinction, estimated by Ruiz-Lapuente et al. (2004) to be $A_V = 1.86 \pm 0.12$, led Krause et al. (2008) to a distance estimate of $3.8^{+1.5}_{-1.1}$ kpc.

Radio measurements of H I absorption to *Tycho* can be used to estimate the distance kinematically through comparison with Galactic rotation curves, with the difficulty that Tycho is located in the outer Perseus arm, where a spiral shock causes a velocity reversal. Tian and Leahy (2011) reported the most comprehensive kinematic measurement and review others to arrive at a distance of 2.5−3.0kpc.

In a recent X-ray study, Hayato et al. (2010) use ejecta radial velocities measured from *Suzaku* and proper motion measurements from *Chandra*, to obtain a distance estimate of 4.0 ± 1.0 kpc. (They also provide a review of measurements by other techniques.) A similar but more detailed analysis based on *Chandra* data alone by Sato and Hughes (2017) arrived at essentially the same distance. In both these studies, determining the distance relies on some assumptions about the geometry, since the proper motions are measured at the rim, while radial velocities are for interior knots.

Proper motions of the outer optical filaments, combined with the shock velocity inferred from the width of the broad Balmer lines that characterize them, lead to closer distances, 2.3–3.1kpc (Chevalier, Kirshner & Raymond 1980; Smith et al. 1991; Ghavamian et al. 2001). While both the proper-motion and velocity-broadening measurements are done for the same outer filaments and are quite precise, the difficulty in this method comes in the shock models that are necessary to infer a shock velocity from the velocity broadening. These must account for energy lost to the acceleration of charged particles at the shock front – still somewhat uncertain (e.g. Heng 2010; Morlino et al. 2013).

Morlino and Caprioli (2012) estimate the distance as ∼3.3 kpc, based on their models to reproduce the extremely faint γ-ray emission from Tycho detected from VERITAS (Acciari et al. 2011) and *Fermi*-LAT (Giordano et al. 2012). Slane et al. (2014) have since developed a more sophisticated hydrodynamic model for the broadband spectrum of Tycho from radio through γ-rays to arrive at a similar distance estimate of ∼3.2 kpc.

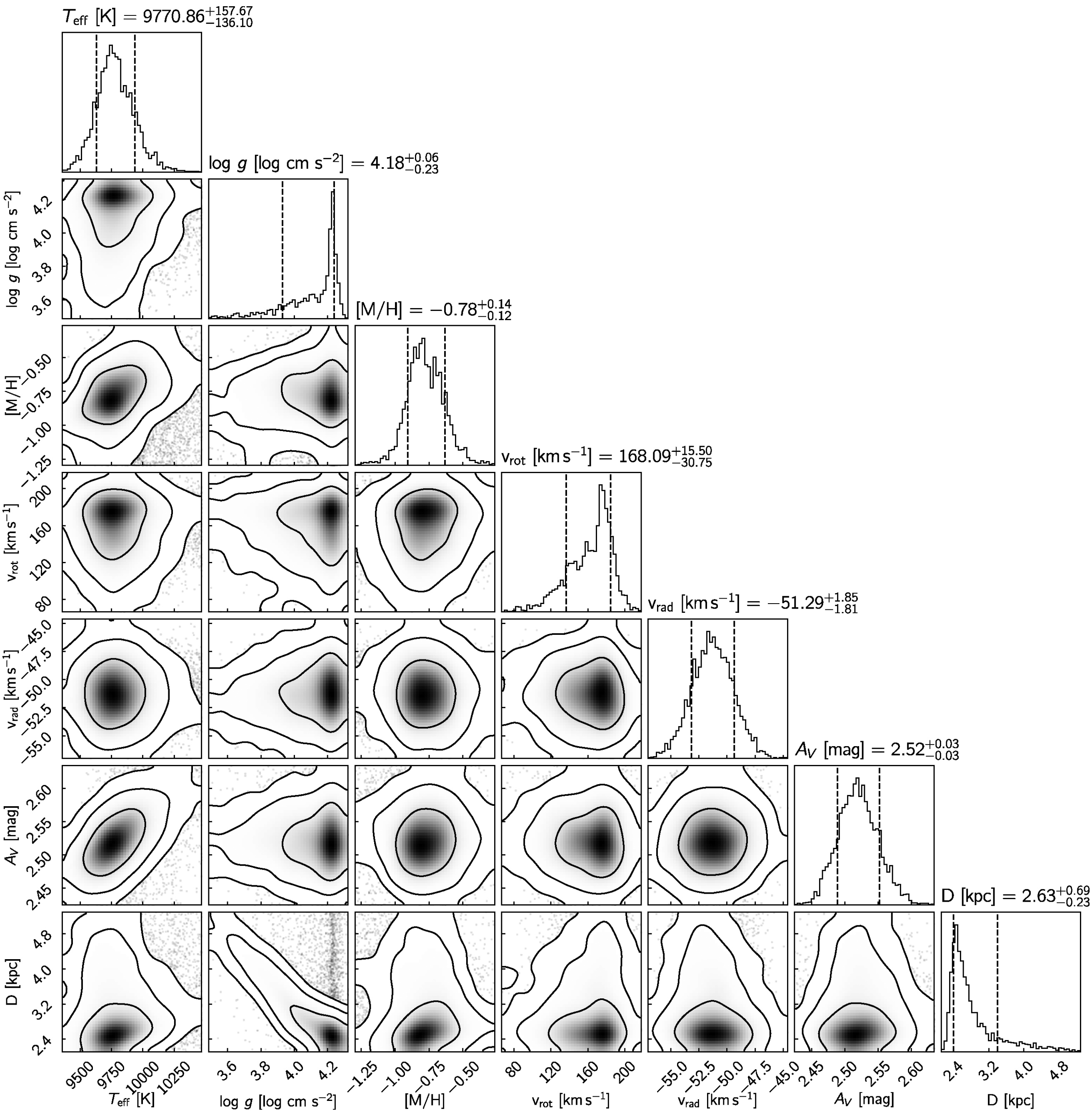


Figure 4. Stellar parameter estimation for Tycho-B using the presented STARKIT model.

A distance range of 2.5–4.0kpc to Tycho, which we have adopted for comparison with Tycho-B in Fig. 7 (discussed below) embraces virtually all of the recent estimates. However, a more precise measure of the distance to Tycho would clearly be valuable.

4.2 Distance to Tycho-B

We have found the luminosity distance to Tycho-B by using the STIS UV spectrum in combination with the optical spectrum from LRIS (Kerzendorf et al. 2013). For modelling the spectrum, we generated synthetic spectra using the STARKIT framework, and then apply Bayesian statistics to obtain the allowed luminosity range, as detailed in Section 3. Since the STIS spectrum is well flux-calibrated, we can then obtain a luminosity distance.

The result is consistent with the stellar parameters presented in Kerzendorf et al. (2013). The distance determination of $2.63^{+0.69}_{-0.23}$ kpc is consistent with Tycho-B being in front of the remnant. However, we note that this distance estimate is very sensitive to the $\log g$ measurement, which we believe carries a larger systematic uncertainty that is not included in the determination. Thus we have tried to independently check our results.

One possibility is to use the extinction-distance relation determined by Green et al. (2018) to obtain an independent distance estimate given our inferred A_V measurement. They use stars as light

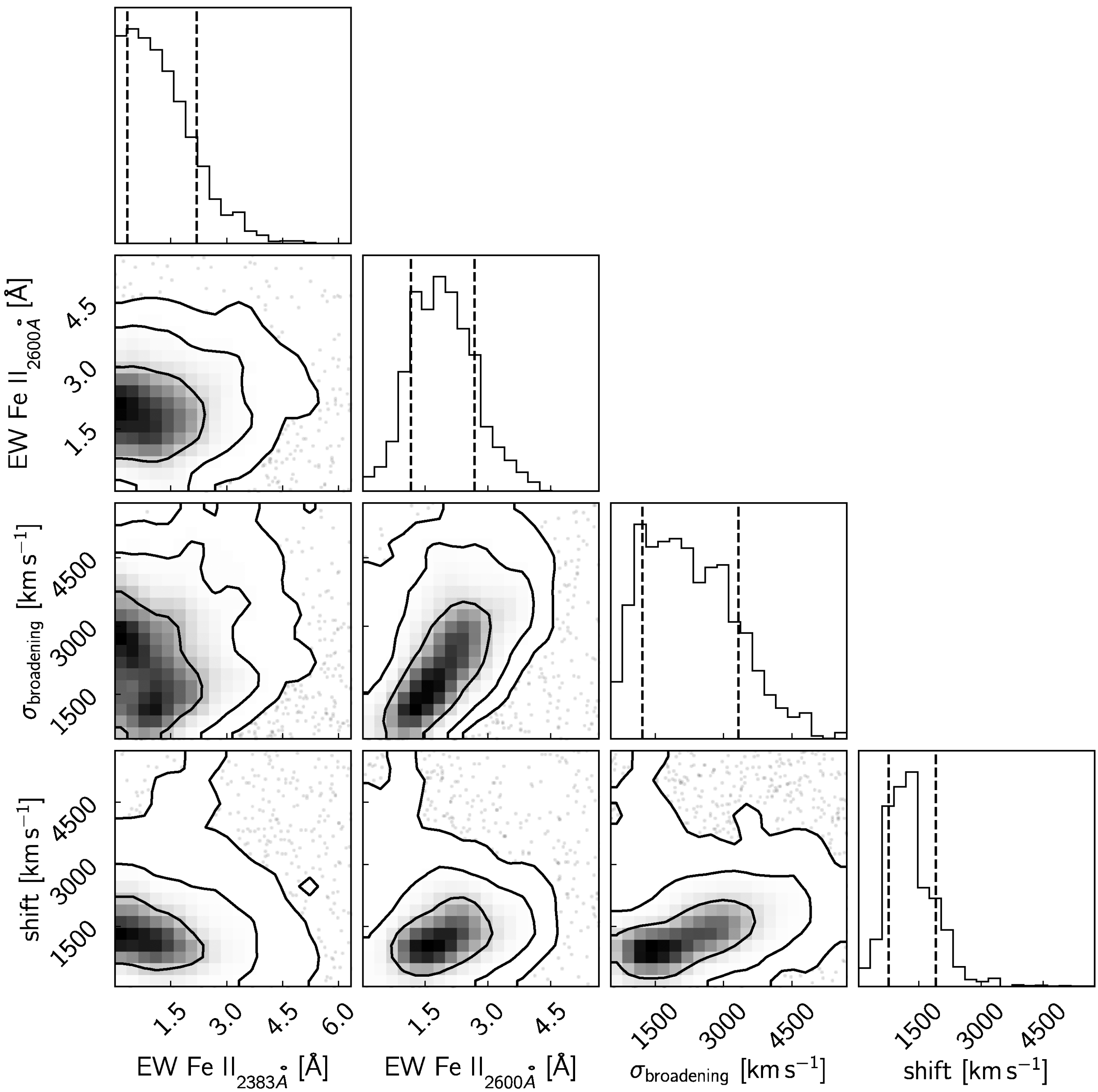


Figure 5. Parameter estimation for the absorption troughs for a model with the star within the remnant marginalized over the stellar parameters.

sources to measure their foreground dust column and infer the distance and brightness of the star by employing probabilistic models. Fig. 7 shows that for our inferred A_V we obtain a distance similar to the luminosity distance. We believe the difference to arise from the various systematic uncertainties that are not directly included in the fit (e.g. the absolute luminosity of the models, the log g sensitivity of the models, etc.). We have also marked the distance uncertainty for Tycho's supernova remnant.

5 SUMMARY

Tycho-B is one of several stars that have been proposed as a progenitor companion for the object that produced Tycho's SN. In order to shed light on this issue, we have obtained UV spectra of Tycho-B with *HST*/STIS. We hoped to use these spectra to identify absorption near 2383 and 2600 Å, as is seen in UV spectra of objects behind SN 1006 that might – depending on the shape of the absorption lines – indicate that Tycho-B was within or behind the Tycho SNR. Our principal findings are as follows:

(i) There is no evidence of broad absorption near 2383 and 2600 Å. Our upper limit on the equivalent width of these absorption features is a few Angstrom (on a 3σ level, see Fig. 5), compared to the ≈15Å EW for the broad lines seen in spectra of the Schweizer–Middleditch star which lies behind SN 1006. This implies either that Tycho-B is in front of Tycho's SNR, or that Fe in the interior of Tycho's SNR exhibits a higher ionization state.

(ii) The spectrum of Tycho-B is consistent with that of a 10 000 K main sequence star, and the detailed stellar parameters are consistent with the analysis in Kerzendorf et al. (2013). Both the luminosity

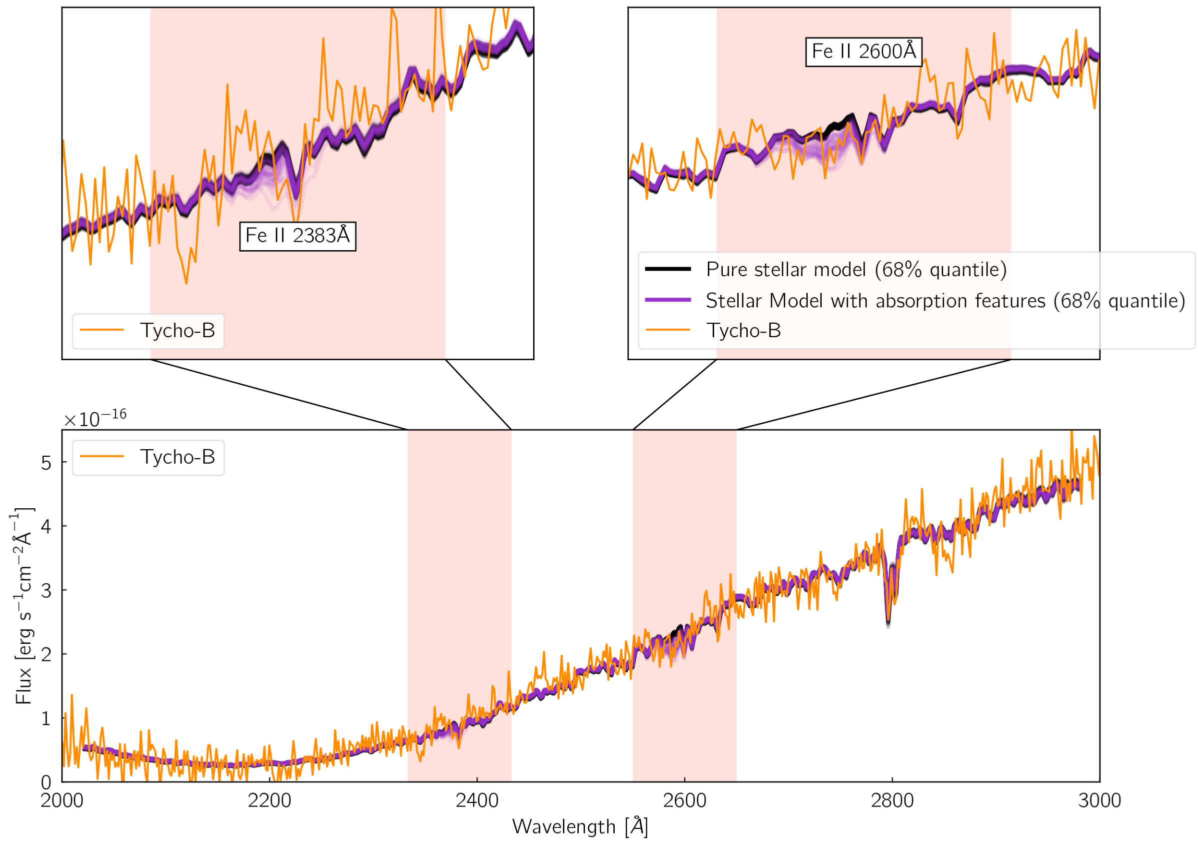


Figure 6. *HST* spectrum of Tycho-B in comparison with the modelling effort. We present the samples from the 68 per cent quantile (for both the models with and without remnant absorption). The cutouts centre on the parts of the spectrum where the Fe II absorption is expected to be.

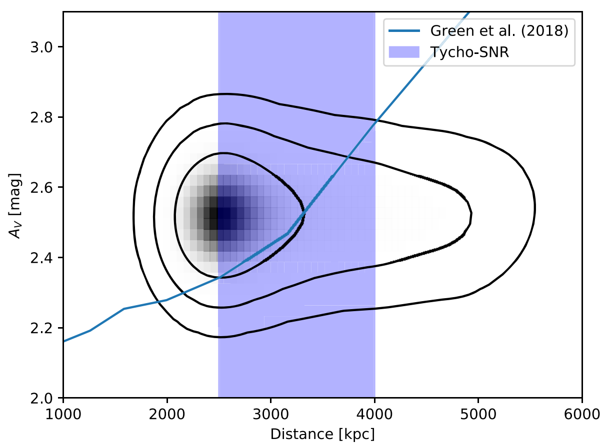


Figure 7. A comparison of distance and extinction inferred from the STIS data (contours mark the 68 per cent, 95 per cent, and 99.7 per cent quantiles) with distance and extinction relationship inferred by Green et al. (2018). We have also marked a conservative distance estimate for Tycho's supernova remnant as discussed in the text.

distance and the inferred A_V imply a distance of ≈2.6 kpc with large uncertainties. While we cannot rule out the possibility that Tycho-B is behind or within Tycho's SNR (and that interior Fe is highly ionized), our analysis favours its being a foreground object.

Overall, our conclusion is that Tycho-B is unlikely to be the progenitor companion of the object that produced Tycho's SNR. Tycho-B has been measured by *Gaia* (*Gaia* DR2 431160569875463936) and shows a distance of 1.9–2.2 kpc and thus is consistent with our conclusion that Tycho-B is a foreground star.

The apparent absence of plausible companions suggests that SN 1572 was not produced by the classical accretion scenario. This conclusion is similar to the one reached by Woods et al. (2017) using a different argument.

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