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No hot and luminous progenitor for Tycho's supernova

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Type Ia supernovae have proven vital to our understanding of cosmology, both as standard candles and for their role in galactic chemical evolution; however, their origin remains uncertain. The canonical accretion model implies a hot and luminous progenitor that would ionize the surrounding gas out to a radius of ~10–100 pc for ~100,000 years after the explosion. Here, we report stringent upper limits on the temperature and luminosity of the progenitor of Tycho's supernova (SN 1572), determined using the remnant itself as a probe of its environment. Hot, luminous progenitors that would have produced a greater hydrogen ionization fraction than that measured at the radius of the present remnant (~3 pc) can thus be excluded. This conclusively rules out steadily nuclear-burning white dwarfs (supersoft X-ray sources), as well as disk emission from a Chandrasekhar-mass white dwarf accreting approximately greater than $10^{-8}\,M_{\odot}\,yr^{-1}$ (recurrent novae; $M_{\odot}$ is equal to one solar mass). The lack of a surrounding Strömgren sphere is consistent with the merger of a double white dwarf binary, although other more exotic scenarios may be possible.

The explosion of Tycho's supernova (SN 1572) in the constellation of Cassiopeia 445 years ago demonstrated definitively that the night sky was not permanent; that is, the Universe evolves. The nature of this supernova, however, was not conclusively determined until recently, when modern analysis of the historical light curve[1], the X-ray spectrum of the supernova remnant (SNR)[2] and the spectrum of light echoes from the explosion that had scattered off interstellar dust[3] showed that it belonged to the majority class of type Ia supernovae (SNe Ia). In spite of these advances, however, the nature of the star that gave rise to this explosion, as well as all others like it, remains unknown. Theoretical models fall into two broad categories: the accretion scenario[4], wherein a white dwarf grows slowly in mass through accretion and nuclear burning of material from a binary companion before explosion; and alternatively, the merger scenario[5], wherein a binary pair of white dwarfs merge after shedding angular momentum through gravitational-wave radiation. Efforts to constrain the nature of the progenitor and any surviving companion star in the vicinity of SN 1572[6,7] have remained inconclusive[8,9]. In particular, there remains significant disagreement on the location of the centre of SN 1572 and therefore the viability of any candidate surviving donor star[10,11]. The extent to which the most commonly cited candidate, Tycho G, stands out from other stars along the same line of sight also remains in question[12,13].

Attempts to detect emission from an individual SN Ia progenitor system have thus far relied largely on searching pre-explosion images of the host galaxies of a few nearby and very recent events[14,15]. These searches have provided some constraints on the presence of hot, luminous progenitors immediately before explosion, as well as optically luminous companions, for these few SNe Ia (in varying degrees of tension with the accretion scenario). Observations from the Kepler spacecraft also ruled out red giant donors for three probable SNe Ia in red, passive galaxies[16], based on the lack of observed shock interaction between the expanding supernova and a Roche-lobe filling companion. However, SNe Ia in passive galaxies are not representative of the 'typical' population[9]. None of these observations can state anything about the earlier evolution of the progenitor. Nor can these constraints be applied to the large sample of resolved SNRs in the Local Group. Conversely, searches for evidence of any luminous progenitor population in X-ray[17,18] or ultraviolet[19,20] emission have placed strong constraints on the total contribution of such progenitors to the observed SN Ia rate in nearby galaxies, but this cannot be inverted to yield information on the origin of individual objects.

Here, we propose an alternative test: to search for a 'fossil' or 'relic' nebula around individual supernovae photoionized by their progenitors. In the accretion scenario, the process that leads to the growth of the white dwarf mass is fusion of hydrogen to helium and further to carbon and oxygen. These accreting white dwarfs must go through a long-lived (approximately 100,000 yr or more) hot, luminous phase of steady nuclear burning on the surface, with effective temperatures of 10^5–10^6 K and luminosities of 10^{37}–10^{38} erg s^{-1} at some point before explosion[21]. Such objects are expected to be significant sources of ionizing radiation[21,22].

For accretion rates lower than approximately $10^{-7}\,M_{\odot}\,yr^{-1}$ (where $M_{\odot}$ is equal to one solar mass), hydrogen fusion is subject to thermal instability, and the nuclear energy is mostly released in the form of classical and recurrent nova explosions[23–25]. Recent measurements of the white dwarf mass in a few nearby recurrent novae have yielded values close to the Chandrasekhar mass limit[26,27], suggesting that these objects may contribute to the production of SNe Ia (if they are carbon–oxygen white dwarfs). However, any accretion onto a white dwarf must also release gravitational potential energy. In the parameter range expected for SN Ia progenitors, accretion proceeds through an optically thick, geometrically thin (Shakura–Sunyaev)[28] disk, which has a well-understood luminosity, temperature and emitted spectrum (see Methods). From this, it can be found that,

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for massive white dwarfs undergoing accretion rates as low as $\sim 10^{-8} M_{\odot}\,\mathrm{yr}^{-1}$, the typical inner disk temperatures and luminosities are of the order of 10^5 K and 10^{35} erg s^{-1}, respectively, rendering them much dimmer (although still notable) sources of ionizing radiation.

Any nebula created by the supernova progenitor will persist until sufficient time has passed for the majority of the gas to recombine[29]. This can be estimated from the hydrogen recombination rate $\alpha_B(\mathrm{H}^0, T)$ (where H^0 represents neutral hydrogen and T is temperature) and from the density n_{ISM} of the surrounding interstellar medium (ISM), assuming the gas is initially nearly wholly ionized (such that the electron density $n_e \approx n_{\mathrm{ISM}}$):

$$\tau_{\mathrm{rec}} = (n_e \alpha_B(\mathrm{H}^0, T \approx 10^4\,\mathrm{K}))^{-1} \approx (100{,}000) \times \left(\frac{n_{\mathrm{ISM}}}{1\,\mathrm{cm}^{-3}}\right)^{-1} \mathrm{yr} \quad (1)$$

where we have assumed 'case B' recombination (that is, ionizing photons produced by recombinations to the ground state are immediately absorbed). If the medium is initially only partially ionized, it will have a longer characteristic recombination timescale, τ_{rec}. Typically, $n_{\mathrm{ISM}} \approx 1\,\mathrm{cm}^{-3}$, so $\tau_{\mathrm{rec}} \approx 100{,}000$ yr. This allows us to constrain the ionization history of supernova progenitors by searching for evidence of their lingering impact on their environment, thus enabling SN Ia archaeology[22], which requires knowledge of the density and ionization state of the ISM in the ~1–100 pc vicinity of known SNe Ia[30].

One way to obtain this information is to use the expanding supernova shock itself as a probe of the surrounding ISM. Tycho's SNR is one of a number of known SNe Ia remnants whose forward shock is traced in part by filaments of Balmer-line optical emission. This arises due to collisional excitation of neutral hydrogen immediately behind the advancing shock, where excitation of cold neutral hydrogen produces a narrow Balmer emission line, while excitation of hot neutral hydrogen formed by charge exchange gives rise to a broad Balmer emission line[31]. The existence of this emission along the eastern and northern periphery of Tycho's SNR demonstrates that the ambient environment around the remnant (and thus, by extension, its progenitor) is at least partially neutral[31,32]. Modelling of both the Hα and the Hβ broad-to-narrow flux ratios from the forward shock, and modelling of the [O III]/Hβ ratio from the photoionization precursor ahead of the forward shock, indicate that the ambient hydrogen must be at least 80% neutral in this region[32,33] (see also Supplementary Information). This strongly constrains the ionizing luminosity from the progenitor before and during the explosion[34–36].

Recently, it has been suggested based on carbon monoxide observations[7] that Tycho's SNR is associated with dense clumps of molecular gas in the same region of the Milky Way, suggesting a thick molecular shell, possibly excavated by a fast, continued outflow from the progenitor. We note, however, that the known age (445 yr), physical size[37] (~3 pc) and ionization timescale ($\log(n_e t/(\mathrm{cm}^{-3}\,\mathrm{s})) \approx 10.5$ for the silicon ejecta)[38] of SN 1572 confidently rule out an expansion into any kind of low-density cavity or dense, massive shell excavated by a progenitor outflow[38,39]. These properties of the SNR are fully consistent with an expansion into an undisturbed ISM with average $n_{\mathrm{ISM}} \approx 0.5$–$1\,\mathrm{cm}^{-3}$ since the time of the explosion. This is very close to the density that the outer shock is running into today. (Although the remnant is also encountering denser gas on the eastern edge, this is not characteristic of the mean density of the environment[40].) Any large-scale modification of the ambient medium around the supernova is in direct conflict with the bulk properties of the SNR (for more details, see Fig. 3 and discussion in ref. [39]). Additional arguments against the existence of any molecular bubble associated with Tycho's SNR include the spatial extent of the observed photoionization precursor, and the marked discrepancy between the velocities of the carbon monoxide and hydrogen Balmer emission lines measured relative to the local standard of rest. These arguments are summarized in the Supplementary Information. We note, however, that even if such a molecular bubble were associated with Tycho's SNR, with an inner radius just outside the present radius of the shock, the low density and ionization state of the gas interior to this point, which is presently being overrun, would still provide the same constraint on the nature of the progenitor before explosion.

The characteristic size of the nebula ionized by the hypothetical hot supernova progenitor is determined by the Strömgren radius (R_S), which scales as[22]:

$$R_S \approx 35\,\mathrm{pc} \left(\frac{\dot{N}_{\mathrm{ph}}}{10^{48}\,\mathrm{s}^{-1}}\right)^{\frac{1}{3}} \left(\frac{n_{\mathrm{ISM}}}{1\,\mathrm{cm}^{-3}}\right)^{-\frac{2}{3}} \quad (2)$$

where $\dot{N}_{\mathrm{ph}}$ is the ionizing luminosity (in photons per second). Note that for variable sources, a weighted average of the ionizing photon luminosity over τ_{rec} is the quantity of interest[41]. The number of ionizing photons emitted per unit energy depends on the shape of the emitter's spectrum; but for photospheric temperatures in the range $2 \times 10^4\,\mathrm{K} < T < 10^6\,\mathrm{K}$, $\dot{N}_{\mathrm{ph}} \approx 10^9$–$10^{10}$ ionizing photons per erg.

For relatively cooler ionizing sources ($T < 10^5$ K), the outer boundary of the ionized nebula is very sharply defined (see blue lines in Fig. 1), owing to the high photoionization cross-section for hydrogen. Therefore, given the ambient density of the surrounding ISM inferred above, the presence of any neutral hydrogen at the forward shock radius of Tycho's SNR ($R_S \approx 3$ pc) places a strict upper limit on the size of the ionized nebula for SN 1572. For an average surrounding $n_{\mathrm{ISM}} < 1\,\mathrm{cm}^{-3}$, this translates to an upper limit on the ionizing photon luminosity of $\dot{N}_{\mathrm{ph}} < 6 \times 10^{44}\,\mathrm{s}^{-1}$. From equation (2), the upper limit on the ionizing source luminosity scales as $\propto n_{\mathrm{ISM}}^2$. However, as explained above, the density of the ISM surrounding SN 1572 is fairly well constrained.

Hotter sources (with effective temperatures T_{eff} greater than 10^5 K) produce higher-energy photons with longer mean free paths, which broaden the boundary between ionized and neutral media. This necessitates using a detailed photoionization simulation to determine the fraction of ionized hydrogen as a function of radius (see Methods). This is illustrated in Fig. 1, from which it is clear that any luminous (approximately greater than 10^{36} erg s^{-1}), high-temperature source would still have produced a greater ionized hydrogen fraction (~20%) than observed at the present radius of the remnant. Here, we have assumed $n_{\mathrm{ISM}} \approx 1\,\mathrm{cm}^{-3}$, approximately

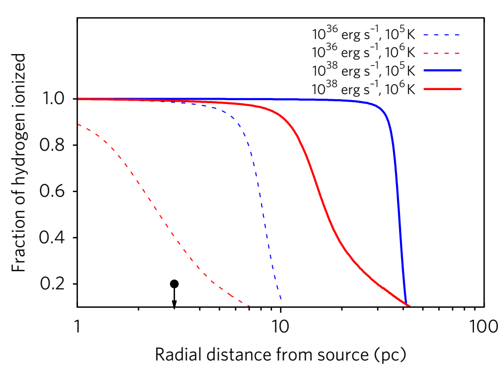

Fig. 1 | Hydrogen ionization fraction as a function of radial distance from the progenitor of SN 1572, for putative objects with different effective temperatures. The solid and dashed lines roughly bracket the range in expected accreting, nuclear-burning white dwarf temperatures and luminosities[42]. Shown in black is the upper limit on the hydrogen ionization fraction at the present radius of the shock.

the observed upper limit. Lower densities would yield larger ionized regions (see equation (2)).

We summarize our constraints on hot, luminous progenitors in Fig. 2, which compares our upper limits on the luminosity as a function of effective temperature with theoretical models of white dwarfs accreting at rates capable of sustaining steady nuclear burning of hydrogen[25]. For comparison, we include parameters for several observed sources[42]. All are confidently excluded. Note that, for putative progenitors with complex accretion histories, any arbitrary trajectory in the Hertzsprung–Russell diagram given in Fig. 2 can be excluded using the same constraint, that is, if it produces too great a time-averaged photoionizing flux. From these results, it is clear that the progenitor of SN 1572 cannot be described by the classic nuclear-burning accretion scenario. A white dwarf accreting at a much higher rate, such that it ejected sufficient mass in a fast wind that might have masked the ionizing flux[43,44], would have strongly modified the surrounding environment, in conflict with the apparent evolution of the shock into an undisturbed, constant-density medium[38]. Slow (~100 km s^{-1}) winds could in principle obscure the lowest-luminosity sources that we otherwise exclude in Fig. 2 (~10^{36} erg s^{-1}) for mass loss rates greater than $10^{-8} M_{\odot}$ yr^{-1} (for example, from a companion on the first giant branch)[45]; however, radio[46,47] and X-ray[48,49] observations have ruled out such winds in the environments of normal SNe Ia[50], and no surviving giant donor consistent with this scenario has been found for SN 1572 (see discussion above).

We can perform a similar experiment using our photoionization simulations, given emission spectra from an accretion disk around a white dwarf. For a Chandrasekhar-mass white dwarf, the threshold for an accretion rate capable of steady nuclear burning is ~$4 \times 10^{-7} M_{\odot}$ yr^{-1} (refs [24,25]). We find that any Shakura–Sunyaev[28] disk with accretion rates exceeding $10^{-8} M_{\odot}$ yr^{-1} onto a Chandrasekhar-mass white dwarf can be confidently excluded. For hydrogen-accreting white dwarfs, this is approximately the threshold accretion rate below which the mass ejected in novae is theoretically expected to exceed that accumulated between outbursts; that is, the white dwarf could not have been growing in mass.[51] Note that, more generally, our constraint on the accretion rate is independent of whether the white dwarf is accreting hydrogen or helium. Thus, the detection of neutral matter in the vicinity of SN 1572 is strongly constraining also for accreting scenarios without surface nuclear burning. In particular, it excludes any nova progenitor with recurrence time shorter than ~50 yr (refs [24,25]).

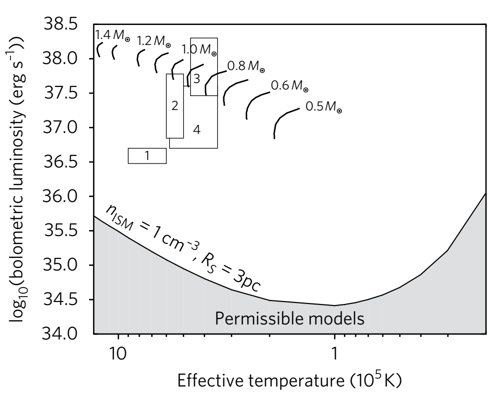

Fig. 2 | Upper limits on the typical luminosity of the progenitor of SN 1572 during the past 100,000 yr. The black lines denote theoretical accreting stable nuclear-burning white dwarf models[25]. The black boxes mark the approximate ranges of temperatures and luminosities inferred for four confirmed close-binary Magellanic supersoft X-ray sources with definitive luminosity measurements[42,74]: CAL 87 (1), 1E 0035.4-7230 (2), RX J0513.9-6951 (3) and CAL 83 (4). Note that the only source that seems to be inconsistent with theoretical models is CAL 87; however, this source is viewed nearly edge-on, and the disk is understood to at least partly obscure the central hot object[75].

To conclude, we rule out steadily nuclear-burning white dwarfs or recurrent novae as the progenitors of SN 1572. This is consistent with recent theoretical work indicating that significant mass accumulation in steadily hydrogen-burning accreting white dwarfs may not be feasible[52]. Models that do not predict a hot, luminous phase before explosion, such as the merger or 'double-degenerate' scenario, remain consistent with our result. This includes 'violent' mergers[53], although such explosions may be expected to be too asymmetric to explain typical SNe Ia[54], including SN 1572[55]. Notably, it has been suggested that some white dwarf mergers may actually produce a short-lived soft X-ray source; this too is excluded by our constraint, although the same theoretical models suggest in these instances that the object may not explode as a SN Ia[56,57]. We also cannot exclude a 'spin-up–spin-down' single-degenerate progenitor model with a spin-down timescale longer than ~10^5 yr for the origin of SN 1572[58–60], although there remain other theoretical and observational challenges for this scenario[9].

Given that the light echo spectrum of SN 1572 has revealed it to be a typical type Ia[3], any plausible model for the origin of the majority of SNe Ia must remain consistent with the constraint outlined here. Similarly strong constraints (or detections) can be obtained for other nearby SN Ia remnants with sufficiently deep observations[22], using the expanding shock to probe the progenitor's environment. This work will open a new path to reveal at last the progenitors of SNe Ia.

Methods

Photoionization models. Given that we are considering relatively high-temperature (>10^5 K) ionizing sources, with correspondingly broader transition regions between ionized and neutral media than given analytically by the classical Strömgren boundary, we model the size of any putative photoionized region using the plasma simulation and spectral synthesis code Cloudy version 13.03 (ref. [61]).

Cloudy determines the gas temperature, ionization state, chemical structure and emission spectrum of a photoionized nebula by solving the equations of statistical and thermal equilibrium in one dimension. The code relies on a number of critical databases for its calculations; notably, tables of recombination coefficients[62,63], and ionic emission data taken from the CHIANTI collaboration database version 7.0 (refs [64,65]).

We assume spherical symmetry in our models with $n_{\rm ISM} = 1$ cm^{-3}, unless otherwise stated. Lower densities would result in only larger nebulae for fixed source temperature and luminosity, and $n_{\rm ISM} \approx 1$ cm^{-3} is the approximate upper bound inferred for the preshock intercloud ISM in the vicinity of Tycho's SNR. We assume solar metallicity for the ISM in the vicinity of Tycho's SNR; the default solar values as defined in Cloudy are taken from ref. [66] with updates to the oxygen and carbon abundances[67,68] as well as those of nitrogen, neon, magnesium, silicon and iron[69]. Modest variations in the metallicity will not greatly affect the radius of any photoionized nebula. Given that the age of Tycho's SNR is $\ll \tau_{\rm rec}$, we assume steady-state models throughout.

We approximate the spectra of nuclear-burning white dwarfs as blackbodies. This provides a reasonable fit to their ionizing emission[19,22,70], with significant deviations arising only far into the Wien tail. For white dwarf accretion disks, we use the ezDiskbb[71] model from the X-ray spectral modelling software package xspec[72] to produce Shakura–Sunyaev[28] disk spectra for any desired white dwarf mass and accretion rate. This sets the shape of the spectrum in Cloudy. We normalize the luminosity, L, of the accretion disk to the rate of gravitational potential energy release (where G is the gravitational constant):

$$L = \frac{1}{2}\frac{G M_{\rm WD} \dot{M}}{R_{\rm WD}} \quad (3)$$

for a given white dwarf mass ($M_{\rm WD}$), radius ($R_{\rm WD}$) and accretion rate ($\dot{M}$). For the white dwarf radius, we approximate numerical results for a zero-temperature white dwarf[73] radius with the relation[17]:

$$R_{\rm WD} = 0.0126\left(\frac{M_{\rm WD}}{M_{\odot}}\right)^{-\frac{1}{3}}\left(1.0 - \left(\frac{M_{\rm WD}}{1.456 M_{\odot}}\right)^{\frac{4}{3}}\right)^{\frac{1}{2}} R_{\odot} \quad (4)$$

We conservatively adopt the radius of an approximately 1.35 $M_{\odot}$ carbon–oxygen white dwarf in producing our limit on accreting objects. Any more massive white dwarf would have a smaller radius and thus larger disk luminosity.

Note that we do not include emission from the boundary layer. For slowly rotating white dwarfs, the luminosity in the boundary layer should be comparable to that of the disk. If the boundary layer is optically thick, this should roughly double the total ionizing luminosity. This is expected on theoretical grounds. However, given the difficulty in matching this to observed cataclysmic variables, we do not include an optically thick boundary layer in our estimates.

Data availability. The photoionization and spectral synthesis code used in this work, Cloudy, is open source and may be downloaded from www.nublado.org. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

T.E.W. led the cloudy simulations and analysis of their results, and was the primary author of the main text and methods. P.G. wrote the supplementary section of the paper, and wrote portions of the main manuscript summarizing the constraints on preshock conditions from the Balmer-dominated shocks. C.B. first suggested this project during the conference 'Supernova Remnants: An Odyssey In Space After Stellar Death' in Crete, and contributed to the text and the interpretation of the analysis. M.G. contributed to defining the simulations setup, analysis and interpretation of cloudy results and to the writing of the manuscript.

Competing interests

The authors declare no competing financial interests.

Additional information

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