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On the nature of Tycho Brahe's supernova

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At the 450 years anniversary of its observation, the supernova named after Tycho Brahe, SN 1572, can be explained in the terms used nowadays to characterize Type Ia supernovae (SNe Ia). By assembling the records of the observations made in 1572–74 and evaluating their uncertainties, it is possible to recover the light curve and the color evolution of this supernova. It is found that, within the SNe Ia family, the event should have been a SN Ia with a normal rate of decline. Concerning the color evolution of SNe Ia, the most recently recovered records reaffirm previous findings of its being a normal SN Ia. The abundance studies from X–ray spectroscopy of the whole remnant point to a nuclear burning of the kind of a delayed detonation explosion of a Chandrasekhar–mass white dwarf. A tentative single degenerate path to explosion was suggested from the exploration of the stars in the field of SN 1572. Though, the origin in a double degenerate is being considered as well. Tycho Brahe's supernova, being the first supernova studied by astronomers, is still the subject of very intensive debates nowadays.

KEYWORDS

cosmology, stars: supernovae: general, SN 1572, supernova remnants, exploding stars

1 Introduction

In this review, we will start with the historical data on the supernova discovered by Tycho Brahe, SN 1572. We give an account of its light curve and cosmological charaterization. We discuss as well the explosion mechanism of the supernova and the binary path leading to the explosion, taking into account the most recent work. This article aims to address what is known about the nature of Tycho's SN. Though, due to constraints on the length, not all the contributions in relation to this topic can be discussed. We will try to present the most recent overall view.

We will begin with an introduction of SNe Ia as calibrated candles. The understanding of SNe Ia as empirical tools in cosmology had an enormous boost at the end of the past century. Pskovskii (1977); Pskovskii (1984) first suggested a correlation between absolute magnitude at maximum and rate of decline of the light curve. The faster the decline of the light curve the dimmer the SN Ia and the slower the decline the brighter the SN Ia. The follow–up of SNe Ia with modern digital CCD detectors, as done in the Calan-Tololo search, confirmed that such correlation had a low intrinsic dispersion. Extensive and accurate observations collected by Phillips, Hamuy and collaborators allowed to build up the mathematical expression. Phillips (1993) first quantified it using a small number of SNe Ia. After that, Hamuy et al. (1996a); Hamuy et al. (1996b) enlarged the study and obtained a more significant fit. The relation has the form:

$$M_{MAX} = a + b\left[\Delta m_{15}(b) - 1.1\right] \tag{1}$$

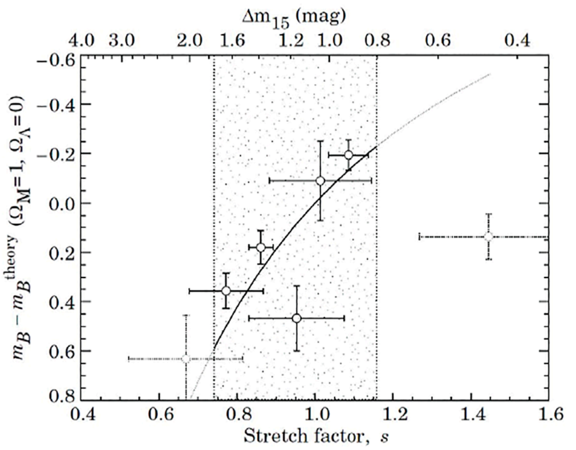

FIGURE 1
m_B magnitudes *versus* the best-fit stretch factor, s, for high-redshift supernovae. The upper axis gives the equivalent values of $\Delta m_{15} = 1.96(s^{-1} - 1) + 1.07$. Figure from Perlmutter et al. (Supernova Cosmology Project) in *Thermonuclear Supernovae* (ed. P. Ruiz–Lapuente et al., 1997). © Kluwer Academic Publishers. Reproduced with permission.

where M_{MAX} is the absolute magnitude at maximum, a and b are constants, and Δm_{15} is the number of magnitudes increased in 15 days after maximum. As the first results were given by Phillips (1993), this is called the Phillips relationship (also Phillips et al. 1999, Ph99 law).

The *Supernova Cosmology Project* used for that maximum brightness–rate of decline of the light curve the so-called *stretch factor*, *s* (Perlmutter et al., 1997; Goldhaber et al., 2001), measuring the amount of broadening or narrowing of the light curve up to 60 days after maximum in relation to a template light curve (see **Figure 1** from comparison of Δm_{15} and s). In this way, they were able to use the corrected to template light curves for cosmology, m_B^{eff}:

$$m_B^{\text{eff}} \equiv m_B + \alpha (s - 1) \tag{2}$$

where α is the best–fit value of the stretch-luminosity slope from the fit to the primary low-extinction subset (Knop et al., 2003)[1].

On the other hand, the *High-z Supernova Search Team* employed the MLCS (*Multicolor Light Curve Shapes*: Riess et al., 1995; Riess et al., 1996) method. Riess et al. (1995) give an alternative way to express the intrinsic luminosity of Type Ia supernovae as related to the rate of decline of the light curve. They fit with an overall shape parameter the evolution in luminosity before maximum to well past maximum. Their parameterization, and the one used by Hamuy and collaborators (1996a;b) give a comparable scale of magnitudes for specific SNe Ia The most recent version by this method is the MLCSk2 (Jha et al., 2007).

Several SNe Ia had been discovered after maximum, so the peak brightness had to be extrapolated by comparison with light-curve templates. These SNe were at distances corresponding to redshifts $0.01 < z < 0.1$. During the 90s, the *Supernova Cosmology Project* and the *High-z Supernova Search Team*, had started to observe SNe Ia at higher redshifts, $0.18 \leq z \leq 0.83$, to measure the evolution of the Hubble parameter, $H(z)$. From two different samples of high-redshift SNeIa and using these different methods of light-curve fitting, the two groups reached the same conclusion: the expansion of the Universe is accelerating (Riess et al., 1998; Perlmutter et al., 1999).

Tycho SN 1572 looked like a normal SN Ia, i. e., did not show to be neither overluminous nor underluminous if the historical records of the SN were fit with the *stretch* relationship for SNe Ia (Ruiz-Lapuente, 2004, hereafter called R04). The light curve shape has been confirmed and the color evolution from a typical SN Ia has been proved in more recent historical studies (Neuhaeuser, 2022).

In recent years, new types of explosions akin to SNe Ia have been observed, which do not belong to the "normal" class, they being either overluminous or underluminous and thus not following the Phillips relationship.

The historical view of Tycho's SN has been expanded with historical research that will be mentioned in **Section 2**. The light curve, color and extinction of the supernova are treated in **Section 3**. Concerning the search for the progenitor and the explosion mechanism, there have been recent revisions and the current state of the question will be addressed in **Section 4**.

2 Historical records

SN 1572 was well observed in Europe (as well as in the Middle–East and Far–East) for almost 2 years. It added a new aspect to the debate at the time over the Aristotelian cosmological views, as it forced to reconsider the immutability of the heavens and the solid nature of the celestial spheres: the "star" gained brightness and lost it during a period of 2 years, but it showed no detectable parallax. According to prevalent views about the heavens, mutability would only happen in the sublunar region. This was even the place where comets were assumed to originate. The appearence of SN 1572 challenged the order of the celestial spheres. The observers who followed it up[2] took sides with respect to established Aristotelian views (Ruiz–Lapuente, 2005). Today we can still use their observations to see whether that supernova would be of use for cosmology in a different way, as a distance indicator if seen by

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[1] This is applied after correcting from extinction as implied by the reddening of the SN Ia. In a more recent version, color changes due to reddening or intrinsic color of SNe are treated equally in the SALT2 standarization (Guy et al., 2007). The coefficients for stretch, x1, and color, c, go respectively in a $\alpha \times x_1 - \beta \times c$ correction to the observed magnitude. (Some more recent parametrizations add additional terms in the equation). There are relations between x1, the stretch s from the *Supernova Cosmology Project* and the Δm_{15}:

$$s\,(SCP) = 1.07 + 0.069x_1 - 0.015x_1^2 + 0.00067x_1^3 \tag{3}$$

$$\Delta m_{15} = 1.09 - 0.161x_1 + 0.013x_1^2 - 0.00130x_1 1^3 \tag{4}$$

[2] The observers who mostly contributed to measure the position and luminosity, Tycho Brahe, Thomas Digges, Thaddeus Hagecius, Michael Mästlin, Jerónimo Muñoz, Caspar Peucer and Johannes Prätorius held very different views on the meaning of SN 1572. A comparison of their measurements and an account of their views is given elsewhere. Recently Neuhaeuser (2022) has provided more data from German, Italian and Czech astronomers of the epoch such as Adam Ursinus (also called Adam Bär), Francesco Maurolyco, Cyprian Leowitz and Georg Busch

observers billions of lightyears away from us. It is indeed possible to have a clear idea of where SN 1572 stands among its class.

After several centuries of questioning the nature of SN 1572, the identification as a Type I supernova came through the revision of the light curve done by Baade (1945) and based on data taken or quoted by Brahe (1603a, b). Before that time, there were still speculations on whether it was a variable star of some kind, a nova (Morgan, 1945) and the suggestion of its cometary nature was still considered (Lynn, 1883). The cometary idea expressed in 1,573 by Muñoz (1573), was based on the fact that the event is aligned with the Milky Way, so its decay in luminosity could be explained if it were a comet born among the stars that would first approach and then move away from us just along the line of sight. Tycho's *stella nova* lies indeed only 49–98 pc above the Galactic plane.

In modern times, its comparison with other SNe allowed its classification as a Type I supernova (Baade, 1945). Later on, this class was shown to contain events of very different nature: those identified with the explosion of white dwarfs (Type Ia, SN Ia) and those corresponding to the collapse of massive stars whose envelope had lost its hydrogen content in the interaction with a binary companion (Type Ib or c, SN Ib or SN Ic, respectively). SN 1572 was of the Type Ia class as discussed by de Vaucouleurs (1985) and by van den Bergh (1993). No further doubts that it is a SN Ia can now be held in view of the X–ray spectrum of its remnant, which clearly differentiates SNe Ia events from SNe coming from the collapse of massive stars (Hughes et al., 1995). A first comparison of its luminosity at maximum with the bulk of SNe Ia would have led to think that it was fainter than normal SNe Ia. van den Bergh (1993) considers whether it could be a peculiar, subluminous SN Ia, like SN 1991bg. However, SN 1572 was heavily obscured. It was reddened by E (B–V) = 0.6 ± 0.04 as it corresponds to the reddening of the stars near its position. After taking into account the extinction undergone across the Milky Way, as well as the measurement of its decline rate, it is concluded that SN 1572 was not a 91bg–like event. Neither was it an overluminous SN Ia like SN 1991T or similars, but rather an event in the middle of the SN Ia class (Ruiz-Lapuente, 2004) (R04).

3 Evidence on visual, color evolution and late decline

The SN 1572 data are compared in R04 to templates using the stretch factor s for the characterization of the rate of decline (Perlmutter et al., 1999; Goldhaber et al., 2001; Nobili et al., 2003). As already mentioned the stretch factor s method was introduced by the *Supernova Cosmology Project* to quantify the decline rate of the supernova from data extending up to 60 days after maximum. Even in absence of a measurement of the brightness at maximum, the method produces a fine description of the supernova within the family of decline rates. It makes sense to use the *stretch* original characterization, as we know what is the reddening suffered by the SN Ia. When we compare magnitude data points and magnitude limits by this method, we clearly see that SN 1572 was not a fast decliner. The best fit corresponds to a stretch factor $s \sim 0.9$. SN 1572 was an event, for instance, very similar to SN 1996X, with $s = 0.889$. A comparison is made in **Figure 2**, with SN 1996X and with the subluminous SN 1991bg ($s = 0.62$). The SN 1572 points are shown together with a template light curve with $s = 0.9$. We see that there is a clear discrepancy with the fast-declining subluminous SN 1991bg. A comparison with the broad light curve of the overluminous SN 1991T shows a similar discrepancy, of the opposite sign.

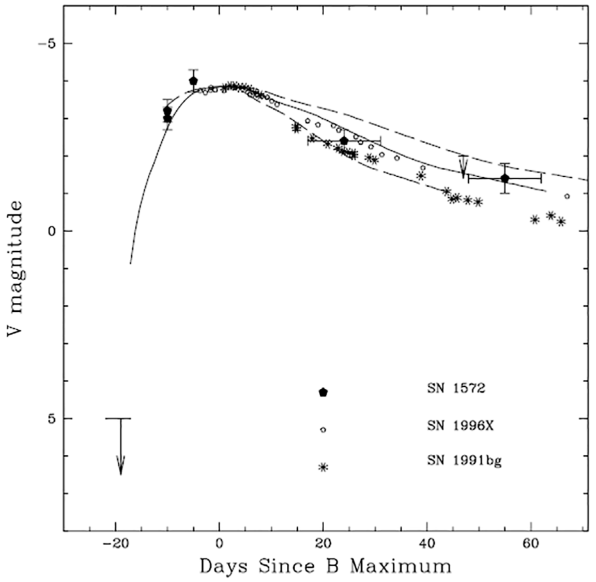

FIGURE 2
The visual light curve of SN 1572 till 60 days. The solid curve is the V light curve of a s = 0.9 SN Ia, which gives the best account for the decline. Such stretch factor is typical of normal SNe Ia. We show for comparison the V light curve of the normal SN Ia SN 1996X, whose stretch factor is s = 0.889 and of the fast–declining SN 1991bg. SN 1572 was significantly slower than SN 1991bg. The light curves plotted in dashed lines are the templates of 91bg–type events and 91T–like events, which depart significantly from the data. Figure in R04. © AAS. Reproduced wih permission.

The late decline of SN 1572, from 100 to 450 days after maximum, which is slow and similar to that of the bulk of SNe Ia, is an additional proof that it was a normal one. SN 1572 declined by 1.4 mag in 100 days, similar to SN 1990N and other normal SNe Ia, with decline rates of 1.38–1.5 mag, also in 100 days. In contrast, SN 1991bg declined again faster over the same period (see Filippenko et al., 1992; Leibundgut et al., 1993; Ruiz-Lapuente et al., 1993; Turatto et al., 1996). SN 1572 is clearly not a peculiar "91bg"–like SN Ia.

Now using the whole light curve, we consider the templates for a normal event with $s = 0.9$ (like SN 1996X), for a subluminous SN 1991bg type and for an overluminous event like SN 1991T, all of them matching the respective available observations. Up to 60 days after maximum, such templates coincide with those of Hamuy et al. (1996b) and with the SCP templates for the same s. At later times, they follow the available late-time photometry (Schmidt et al., 1994; Salvo et al., 2001).

As reported in R04, the fit of the SN 1572 data to the $s = 0.9$ template has an acceptable χ^2 of 14.44 for 10 degrees of freedom, whereas the fit to the $s = 0.62$ template of a fast-declining, subluminous SN Ia (SN 1991bg) has a χ^2 of 53.55 for 3 degrees of freedom (the two premaximum points and the last four points having been omitted due to the lack of data for such stages, in those subluminous events), which is exceedingly high. At the opposite end,

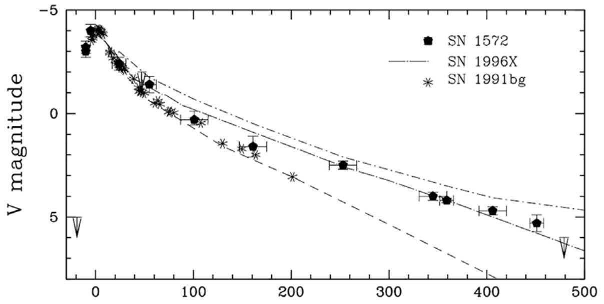

FIGURE 3
The visual light curve of SN 1572 till 500 days. Its late rate of decline is the one of normal SNe Ia. It is very similar to the decline of the s = 0.889 SN 1996X. The visual data of SN 1991bg and the template light curves of this SN Ia and SN 1991T are shown for comparison. Figure in R04. © AAS. Reproduced with permission.

the fit to the $s = 1.2$ template, for slow-declining, overluminous SN Ia like SN 1991T, has a χ^2 of 82.99 for 10 degrees of freedom, which is also too high.

We show in **Figure 3** the total visual light curve of SN 1572, extending to almost 500 days after maximum light, together with the SN 1991bg and SN 1991T templates. The supernova had not yet leveled-off at 480 days past maximum, according to the last upper limit given by Tycho Brahe. It probably leveled-off later, at around 500 days, since there is a light echo of the SN produced by dust clouds nearby, discovered by Krause et al. (2008).

The production of echos depends on the distribution of the clouds, both with respect to the SN and to the observer. So, for instance, in SN 1986G, though being heavily reddened, no echo was observed (Schmidt et al., 1994). SN 1991T and SN 1998bu have shown a slowing down in the V magnitude rate of decline at some 400 days after maxmum, that being due to light echos (Schmidt et al., 1994; Cappellaro et al., 2001). The leveling-off took place at 500 days for those SNe Ia, at some 10 mag from maximum. That, in the case of SN 1572, similar to SN 1998bu, would place the leveling at V = 6 mag, approximately at the limit for the naked eye. SN 1998bu is, in fact, a SN Ia very similar to SN 1996X and SN 1572, its reddening being $E\,(B-V) = 0.32 \pm 0.04$ mag only (Hernandez et al., 2000; Cappellaro et al., 2001), which is half the reddening of SN 1572. One could say that SN 1998bu is a Tycho Brahe with half the extinction suffered by the historical SN 1572. (See next subsection about the similarity of SN 1572 and SN 1996X and SN 1998bu as shown in the spectrum observed in the echo).

In addition, the late light curve of SN 1572 tells us of the energy deposition due to the decay of ^{56}Co to ^{56}Fe in the SN ejecta. The decline being slow points to the explosion of a Chandrasekhar-mass white dwarf and the late decline in V is indicative of a significant deposition of energy by the positrons produced in the decay $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + e^{+}$. Indeed, from 200 days after the explosion, the positrons become the main luminosity source. Departure from full positron trapping in the ejecta is always observed, the reason being incomplete confinement of the positrons and/or incomplete thermalization of their energies. Several causes can produce diversity in the late-time SN light curves: differences in the nucleosynthesis yields and the kinematics of the ejecta, degree of mixing and configuration and intensity of the magnetic field (see Ruiz-Lapuente and Spruit (1998)). It is found that departures of the order of 10%–15% from full trapping of the positrons at 400 days time can be explained by the distribution of radioactive material, but larger departures, of the order of 30%–40% or more, require a lack of confinement of the positrons by the magnetic field or even an enhancement of their escape due to a radially combed magnetic field. In the particular case of SN 1991bg, the very fast drop of the light curve indicates not only an ejected mass below the Chandrasekhar mass but also the absence of a tangled magnetic field.

Milne et al. (1999) made a comparison of the predictions from several explosion models for SNe Ia with a sizeable sample of bolometric light curves. No bolometric light curve for SN 1572 exists, the data being only for the V band, but we can draw analogies with SNe Ia for which we know the bolometric data.

As said above, the late decline of SN 1572 is an important proof, confirming that Tycho's SN falls in no way within the estimated 16% (Li et al., 2001) of intrinsically subluminous SNe Ia. Such low-luminosity class likely arises from a peculiar type of SNe Ia explosions, likely ejecting a smaller amount of mass than normal SNe Ia (Ruiz-Lapuente et al., 1993).

3.1 Light echo of SNe Ia

Sometimes it is possible to know details about a SN Ia long after its light has gone away (see **Figure 4**), through the study of the echo coming from dusty regions around the supernova. The light traveling to a dusty region and beeing scattered and absorbed and re-emitted can take some hundred years to arrive. This is the case for Tycho's SN.

Through the study by Krause et al. (2008), we know that the supernova was a normal one (Krause et al., 2008; Usuda et al., 2013). The spectrum taken of the echo reveals the ion absorptions in full detail and it fits perfectly with a normal SN Ia. Moreover, that paper establishes that the spectrum of SN 1572 matches the comparison spectra of four well observed normal SNe Ia (1994D, 1996X, 1998bu, 2005cf) (Krause et al., 2008). That coincides with the conclusions derived from the light curve (R04).

In the same way that the light curves of superluminous SNe Ia and subluminous SNe Ia differ, the first ones being brighter and slower in their rise and decline while the second ones being less luminous and faster in decline, they also differ in spectra. Superluminous SNe Ia lack a well defined Si II λ 6,355 Å absorption feature at maximum light, though the subsequent evolution is similar to normal SNe Ia. On the other hand, subluminous SNe Ia show a characteristic absorption near 4,200 Å atributed to Ti II, near maximum light.

The spectrum coming from the echo represents those of added epochs corresponding to extent of the scattering cloud. So, typically one compares the echo spectrum with the spectra of a SN Ia time averaged over the brightness peak of the light curve. The dominating characteristics are those of the brightness peak, though it is reasonable to make the weighting by brightnesses of the spectra from 0 to 90 days after explosion, as it is done for several SNe Ia spectra derived from echoes.

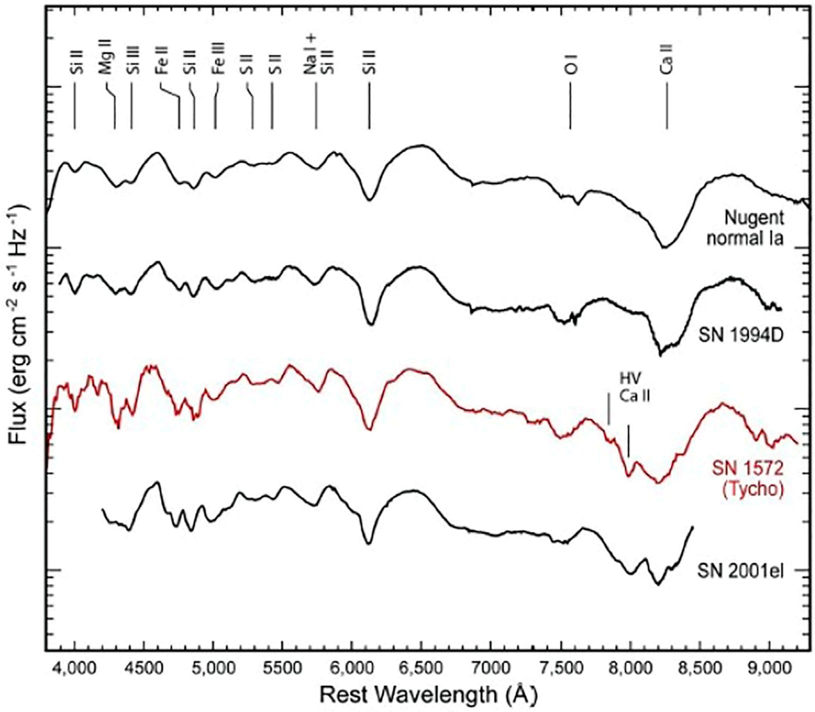

FIGURE 4
Spectrum of the light echo of SN 1572 compared with other normal SNe Ia. The spectra are weighted averages around maximum light. Figure from Krause et al. (2008). Courtesy of T. Usuda. © Springer Nature. Reproduced with Permission.

3.2 Reddening and color

The most direct estimate of the interstellar reddening in the direction of Tycho's SNR is provided by the measurement of the reddening and extinction of the stars close to the centroid of the remnant and at similar distances. The distance to Tycho's SN is in the range of 2–4 kpc (de Vaucouleurs (1985) reviewed values obtained by various methods and they lie in this range). An estimate from Tian and Leahy (2011) based on the modeling of the kinematics of the region gives 2.5–3.0 kpc. The stars near the centroid have average reddenings of $E\,(B-V) = 0.6\pm\ 0.04$ mag. The quoted value comes from the program to search the companion stars of Galactic SNeIa (Ruiz-Lapuente et al., 2004, hereafer RL04). The candidate stars for SN 1572 are within an angular distance from the centroid of the remnant including the uncertainty on the site of the explosion plus the shift in position corresponding to traveling perpendicularly to the line of sight for 431 years, at the velocities expected for the fastest moving companions.

The stars were modeled to obtain the stellar atmosphere parameters T_{eff}, $\log g$ and [Fe/H], plus the distance and $E\,(B-V)$. Radial velocities were measured from the spectra. The surveyed stars cover 35% of the radius of the remnant, and their reddenings span from $E\,(B-V) = 0.50$ mag to $E\,(B-V) = 0.8$ mag, the values increasing with the distance.

The mean reddening above gives an extinction $A_V = 1.86 \pm 0.12$ mag, adopting a R_V of 3.1 (Sneden et al., 1978; Ricke and Lebofsky, 1985). The Galactic extinction data from COBE/DIRBE (Drimmel and Spergel, 2001) give $A_V = 1.77$ mag in that direction, the maximum Galactic extinction there being $A_V = 1.90$ mag. Therefore, the extinction measured at the distance of SN 1572 does agree with the COBE/DIRBE values. Once the apparent brightness is corrected for extinction, it confirms Tycho's SN as a normal SN Ia and not a subluminous one.

The historical records on the color evolution of SN 1572 can equally be corrected for reddening and obtain the intrinsic color evolution. Two months after maximum light, all SNe Ia show a similar evolution in color, and there is a well established law, with low intrinsic dispersion, valid for the period froom 30–90 days, studied by Phillips et al. (1999) and based on the work of Lira (1995):

$$(B-V)_0 = 0.725\,(\pm 0.05) - 0.0118\,(t_V - 60) \tag{5}$$

where t_V is the time from visual maximum.

Two months after discovery, the color of SN 1572 was reported to be similar to that of Mars and Aldebaran, which means that $B-V$ was in the 1.36–1.54 mag range. Other color estimates, previous and subsequent to this one, are given in Table 2 of R04. New historical records have been recently added by Neuhaeuser (2022). Based on the observations of Adam Ursinus, Georg Busch and Cyprian Leowitz, this author asserts that by the end of November the supernova appeared withish or silver, becoming yellowish at the end. These new three points confirm that the SN could not be of the SN 1991bg type, since it should have been reddish in that case. Instead, the points fall where they are expected for a normal SN Ia.

After correction of the observed colors for our measured reddening of $E\,(B-V) = 0.6 \pm 0.04$ mag, the intrinsic color at 55 ± 10 days becomes $(B-V)_0 = 0.76 \pm 0.24$ mag, in very good agreement with the expected $(B-V)_0 = 0.78 \pm 0.15$ mag for the given epoch, thus fitting very well in the Ph99 law above. Nobili et al. (2003) have shown that the color evolution of the bulk of the SNe Ia does follow the law, with only a low dispersion of 0.1 mag in the tail.

Before maximum, the corrected color of SN 1572 would have been $(B-V)_0 = 0.22 \pm 0.29$ mag, which is consistent with the fact that normal SNe Ia have $(B-V)_0 \sim 0$ mag. In contrast, SN 1991bg, as well as other subluminous SNe Ia, clearly deviate from the standard color evolution at early epochs also, they being intrinsically redder at maximum, with $(B-V)_0 = 0.6$ mag (Leibundgut et al., 1993; Ph99). Additionally, the color evolution for a $s = 0.9$ SN Ia agrees well with the SN 1572 data.

In the nebular phase, at 175 days after maximum from Tycho Brahe's records, the SN went back to a white color. Such behaviour, once the correction for extinction is made, is consistent, once more, with that observed in normal SNe Ia. This takes into account uncertainties in the color estimates and includes the new records above.

In R04 the visual absolute magnitude of Tycho's SN is estimated as:

$M_V = -17.72 - 5 \log (d/3.5 \text{ kpc})$ - A_V mag. If corrected for $A_V = 1.86 \pm 0.12$ mag, that gives: $M_V = -19.58 - 5 \log (d/3.5 \text{ kpc}) \pm 0.42$ mag.

De Vaucouleurs (1985) gives as the most likely estimate of the distance to Tycho Brahe's SN: $d = 3.2 \pm 0.3$ kpc. Adopting 3.2 kpc for the distance, we have an absolute visual magnitude $M_V = -19.38 \pm 0.42$ mag. More recently, however, new discussions of the distance sets it to $d = 2.7 \pm 1$ kpc. This estimate comes from the growth of extinction towards higher distance in the field. As measured from stars in the *Gaia DR2* which have measured stellar parameters and colours. From those stars one can track the reddening *versus* distance towards the direction of SN 1572. It is consistent with other estimates mentioned later on. The absolute magnitude of SN 1572 at maximum should be $M_V = -19.02 - 5 \log (d/2.7) \pm 0.42$ mag, which compares well with $M_V = -19.12 \pm 0.26$ mag, the mean magnitude from the Calan Tololo sample (Hamuy et al., 1996a).

4 On the explosion mechanism and progenitor of Tycho's SN

After Baade (1938), Baade (1945a) and Baade (1945b) identified the "nova" B Cas, based on the light-curve data in Tycho Brahe's *Progymnasmata*, as a Type I supernova, he remarked (1945a,b) that no expanding shell had been detected at the position where the supernova flared up.

Exploration of the sky at radio wavelengths, about a decade later (Hanbury Brown and Hazard, 1952; Shakeshaft et al., 1955; Baldwin and Edge, 1957) did locate such nebula at positions compatible with that given by Baade, within the observational errors. Studies of Tycho's SNR at all wavengths have followed, now covering the full range from radio waves to γ-rays.

Especially significant have been the X-ray observations made with the *ROSAT* (Hughes, 2000), *XMM-Newton* (Decourchelle et al., 2001) and *Chandra* (Hwang et al., 2002; Katsuda et al., 2010) satellites. Namely, from the *XMM-Newton* data (Decourchelle et al., 2001), it was found that the chemical abundances and their distribution inside the SNR were those expected from a SN Ia. From the good correlation between the images in the Si XIII K line and the Fe XVII L line, they deduced that some fraction of the inner iron layer had been well mixed with the outer silicon layer.

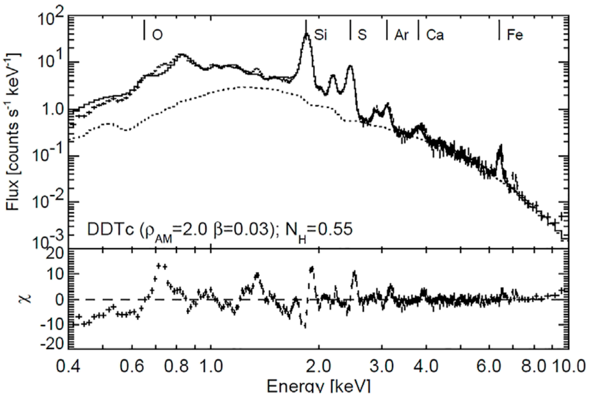

FIGURE 5
Comparison between the emission of the ejecta from a delayed detonation model (**Figure 7** of Badenes et al., 2006) and the spatially integrated spectrum of region B. Courtesy of C. Badenes. © AAS. Reproduced wih permission.

Based on the increasingly detailed data, at all wavelengths, on the morphology, dynamics and chemical composition of Tycho's SNR, there has been physical modeling to infer the explosion mechanism and the nature of the progenitor system of the SN.

Badenes et al. (2006), used X-ray observations from *XMM – Newton* and *Chandra* to test different explosion models and found that the fundamental properties of the X-ray emission in Tycho were well reproduced by a one-dimensional delayed detonation model of a Chandrasekhar-mass white dwarf (see **Figure 5**), interacting with an ambient medium of density $\rho_{AM} = 2 \times 10^{-24}\, g\, cm^{-3}$. There is stratification of the chemical composition, which points to a supersonic burning front. Kozlova and Blinnikov (2018), from hydrodynamical calculations of the X-ray spectrum of Tycho's SNR and comparison of the model with *Chandra* high-resolution images, also conclude that a delayed-detonation model expanding into a uniform interstellar medium is the preferred one for this SNR. The fit of this model gives as best distance 2.8 ± 0.4 kpc. Earlier, Williams et al. (2017), from 3D measurements of the velocities of various ejecta knots using *Chandra* X-ray observations over a 12 years baseline, had equally found that delayed-detonation models are favored.

Badenes et al. (2007), by comparing their models for the evolution of the SNRs with the observations of several remnants of the Ia type, Tycho's SNR among them, find incompatibility with the pre-supernova models where there is emission of strong, optically thick winds from the progenitor system of the supernova. Such winds would excavate large, low-density cavities around the progenitors and that would be incompatible with the dynamics and the X-ray emission of these SNRs. Chiotellis et al. (2013) find that an uniform ambient density cannot simultaneously reproduce the dynamical and X-ray emission properties of Tycho. A better fit is provided by models in which the remnant was evolving within a dense but small wind bubble. The wind bubble might have different origins, including a sequence of nova explosions or a double-degenerate origin.

Sato et al. (2019) analyse the clumpy structure of Tycho's SN remnant. Their genus statistic analysis supports a scenario in which the observed structure of the SN Ia remnant arises from initial clumpiness in the explosion (see **Figure 6**). At present, the cause of the initial ejecta clumping in SNe Ia is found by these authors to be still theoretically unclear and they expect it to gradually become more clear with a 3D simulation covering from the explosion to the remnant phase. The most recent 3D study of the velocity of 59 clumpy, metal-rich ejecta knots, together with the proper motions, estimate a new expansion center of the SNR, at ~6 arcsecs from the geometrical center (Millard et al., 2022). These authors also find that the southeast quadrant expands faster than the rest of the SNR, therefore confirming some degree of asymmetry in the expansion of the ejecta.

Yamaguchi et al. (2017), adopting again a delayed detonation model for a Chandrasekhar-mass white dwarf, explain an iron-rich knot located along the eastern rim of the remnant, surprisingly with no emission from Cr, Mn or Ni (which implies mass ratios $M_{Cr}/M_{Fe} < 0.023$, $M_{Mn}/M_{Fe} < 0.012$ and $M_{sNi}/M_{Fe} < 0.029$) as originating from a region having reached peak temperatures of (5.3–5.7) $\times 10^9$ K only, with a neutron excess $\lesssim 2.0 \times 10^{-3}$, which corresponds either to incomplete Si burning or to an α-rich freeze-out regime, which excludes the dense core of the white dwarf as its origin and points to a region near the boundary of the core as the site of production of the knot.

As we have seen, the delayed detonation mechanism in a Chandrasekhar-mass white dwarf appears to be the one that best explains the overall characteristics of Tycho's SNR in the analysis done by various authors. In the delayed detonation models, C is ignited close to the center of the white dwarf when, due to the accretion of mass from a close binary companion, the central density reaches $\simeq 2 \times 10^9$ g cm^{-3} and the temperature rises to $\sim 10^9$ K. Burning then propagates subsonically (a deflagration) outwards, causing the layers ahead of the burning front to expand. Hydrodynamical instabilities make the burning front turbulent. When some fraction of the star has already been burned and the front reaches regions having densities below some critical value, the front becomes supersonic (a detonation), sweeping the rest of the star up to the surface.

Growth of a C + O white dwarf up to the Chandrasekhar mass by accretion of material from a companion star in a binary system results from a comparatively slow mass transfer (capture of material from the stellar wind of the companion or from a stream due to Roche-lobe overflow by the mass-donor star). Faster mass transfer would happen in the merging with another C + O white dwarf, although it should not be too fast to avoid C ignition close to the surface of the accreting white dwarf before the Chandrasekhar mass is reached. If the explosion would immediately follow the merging, it would hardly have the characteristics of most SNe Ia. If there were a sufficient delay between merging and explosion (MED, see Soker 2019a; Soker 2019b; Soker 2022), however, the exploding object might have becomed a Chandrasekhar-mass white dwarf and then undergo a delayed detonation. Recent work (Neopane et al. 2022) has shown that double-degenerate mergings can actually produce highly magnetized, uniformly rotating white dwarfs, a fraction of them with masses close to the Chandrasekhar mass, which should then explode *via* the delayed-detonation mechanism. Then, although delayed detonation models seem consistent with a single degenerate path to explosion, they can occur as well, if a sufficient delay between the merging of two white dwarfs and the explosion takes place, in the double degenerate scenario.

In fact this DD-MED mechanism is the equivalent in the DD case to the spin up/spin down from Di Stefano et al. (2011) applied with the accretion from a non-degenerate star (SD path). The SD spin up/spin down models can leave a very faint companion. Such faint companion would be too faint to be catalogued in the *Gaia* data releases or in the *Hubble Space Telescope* images taken of the field thus far.

The search for a surviving companion of SN 1572 has been a survey of the stars located not too far from the present geometrical centroid of the remnant, at distances within the estimates for that of the SNR, looking for unusually high tangential and radial velocities, photometric and spectroscopic peculiarities and possible excess of Fe-peak elements at the surface (Ruiz-Lapuente, 1997; RL04).

In the single degenerate channel, the surviving companions of the explosion can, in principle, be at any stage of thermonuclear evolution: main sequence, subgiant, giant or supergiant stars (see Wang and Han, 2012; Maoz et al., 2014; Ruiz-Lapuente, 2014; 2019; Soker 2019a for reviews). They could also be hot subdwarfs (Bauer et al., 2019; Meng and Li, 2019; Meng and Luo, 2021) or fainter objects as mentioned above (Di Stefano et al., 2011). Hydrodynamic simulations of the impact of the SNe Ia ejecta on a non-degenerate companion of any type predict that such stars will survive the explosion after being stripped of some of their mass, heated, and their surfaces possibly contaminated by the slowest moving SN ejecta. The binary system being disrupted, the companions should be ejected at their orbital velocities, plus some kick from the impact of the SN material. In the double degenerate scenario there will be no surviving companion.

The first survey (RL04) (see **Figure 7**) included a number of stars smaller than the ones made later on. Spectra and photometry of all the stars were obtained with several telescopes. Images were taken with the *Hubble Space Telescope*. Radial velocities were measured from the spectra, and proper motions from the *HST* images. Spectral types and luminosity classes were determined by modeling the spectra. Comparison with the photometry then gave the distances to the sampled stars. One star, a subgiant, was a 3σ outlier in radial velocity, as compared with the stars at the same distance and position on the sky. The star, labelled Tycho G (see **Figure 7**), was an outlier in proper motion as well, and its metallicity showed that it was not a halo star. It was therefore proposed, based on its kinematics, as the likely surviving companion of SN 1572.

High-resolution spectra of the star above were later obtained with the *HIRES* spectrometer on the *Keck I* telescope. That allowed an accurate determination of the chemical abundances, in addition to a refinement of the stellar atmosphere parameters and a more precise measurement of the radial velocity. Low-resolution spectra of other stars in the Tycho field were also analyzed to determine their spectral types, with good agreement with the results of RL04.

Kerzendorf et al. (2009) had remarked that if a companion star were rotating synchronously with the orbital motion (rotation period equal to the orbital period), it should be rotating faster than the proposed candidate. González Hernández et al. (2009) had already argued that the interaction with the SN ejecta can slow down

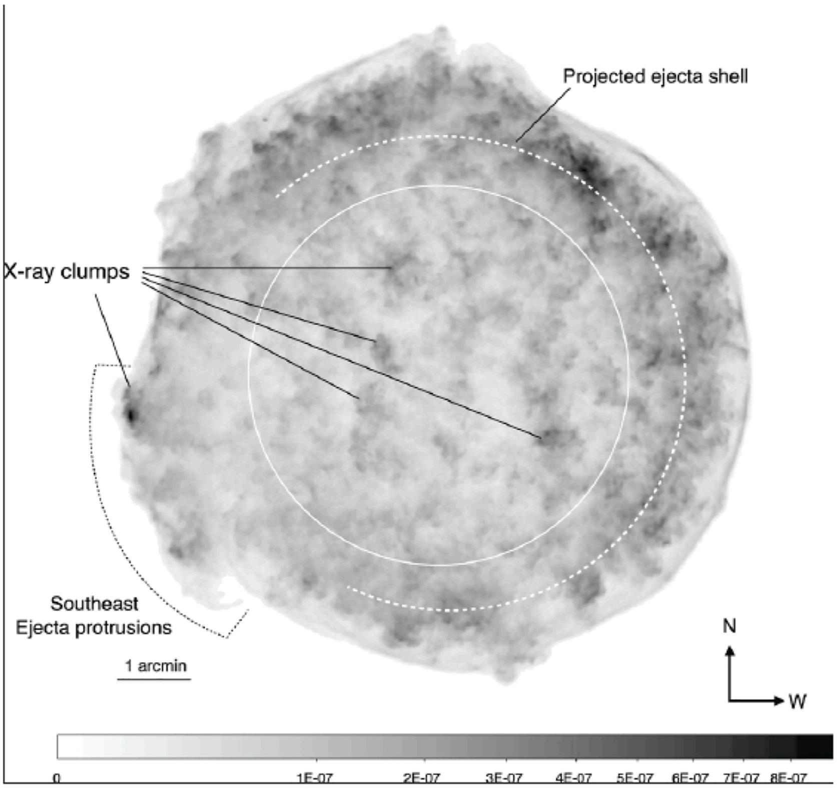

FIGURE 6
Figure 2 in Sato et al. (2019). Flux image (1.76–4.2 keV) of Tycho's SNR observed in 2009 by Chandra. The central region (inner white circle) of the remnant has been used for the genus statistics. The southeast ejecta protusions can be seen as well in the Figure. Courtesy of J.P. Hughes. © AAS. Reproduced with permission.

the rotation. Liu et al. (2013) and Pan et al. (2014) later showed, from hydrodynamical simulations, that the rotational velocity can indeed be much reduced by the collision.

A number of works have been devoted to the possible companions of Tycho's SN remnant. In Kerzendorf et al. (2013), attention was paid to a fast-rotating star of the spectral A type, located close to the geometrical center of the SNR, labelled Tycho B (see **Figure 7**). Kerzendorf et al. (2018), from UV spectra obtained with the *Hubble Space Telescope*, concluded that it rather is a foreground star. The idea was that if there were enough Fe II in the SNR and the star were inside it, the spectrum would show blueshifted absorption lines. If it were behind the SNR, in the background, the lines would be both blueshifted and redshifted, as it is the case with the Schweizer-Middleditch star, in the background of SN 1006. No Fe II absorption lines are seen in the spectrum of star B, which by having a surface temperature $T_{\mathrm{eff}} \sim 10{,}000$ K, should have significant UV emission. From that, Kerzendorf et al. (2018) conclude that either star B is in the foreground or there is not enough Fe II in the SNR, the material being more highly ionized. *Gaia DR3* parallaxes place Tycho B well in the range of distance of the SNR. Ihara et al. (2007) suggested that Tycho E could be the companion of SN 1572 on grounds of absorption seen in the spectra. But this star clearly seems behind the Tycho Brahe's SN (see the **Appendix**). As we mention later, both Tycho B and Tycho E orbits do not look perturbed by an impact.

Bedin et al. (2014) measured the proper motions from *HST* images of a large sample of stars around the center of Tycho's SNR. The chemical abundances of the candidate star Tycho G were calculated in González Hernández et al. (2009), Kerzendorf et al. (2013) and Bedin et al. (2014). The Ni/Fe ratio would point, at most, at moderate or low pollution of the companion of the SN. However, that is what is predicted by the models of Pan et al. (2014): the captured material would be much diluted in the convective envelope of a subgiant star.

The advent of the *Gaia DR2* opened a new space for the definitive exploration of the candidate stars to companion of Tycho Brahe's SN. Ruiz-Lapuente et al. (2019) used the parallaxes from the *Gaia DR2* to reassess the distances to the stars in the Tycho field. The orbits of the stars were also calculated. No orbital peculiarity is seen in Tycho B nor in other candidates stars that had been proposed. The star in RL04 is the most dynamically peculiar in the sample, but there is no real proof that it is the surviving companion it has been looked for. In order to do a full update of this research, in this review the same analysis using now the most recent *Gaia* data is done, those from the *Gaia DR3*. The results, which are shown in the **Appendix**, do not change the conclusions from the 2019 paper using *Gaia DR2*. The proper motions of the stars are similar (though not identical) to those from *Gaia DR2*. The parallaxes are better determined. Neither Tycho B nor Tycho E have a peculiar orbit. The only star somehow eccentric and with a proper motion and V_R

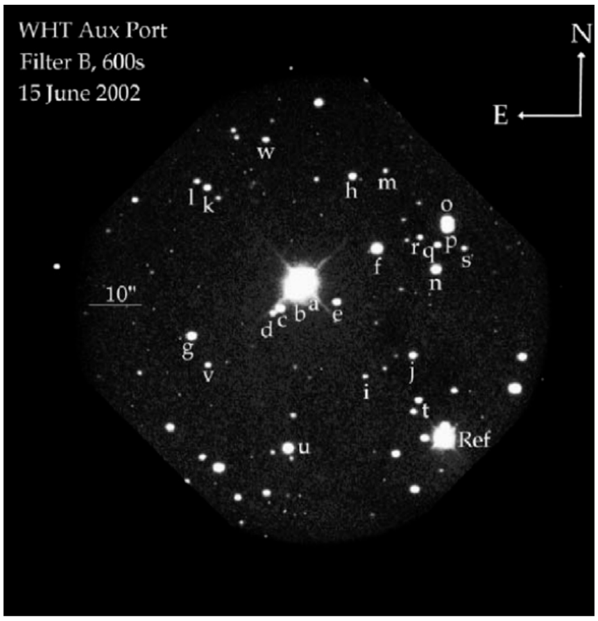

FIGURE 7
Image from the Auxiliary Port at the William Herschel Telescope of the center of the field of SN 1572. It reveals that it is far from being a crowded field. The initial search area in RL04 covers a radius of 0.65 arcmin around RA = 00 h 25 min 19.9 s, Dec. = 64^{O} 08′ 18.2″ (J2000) (the Chandra geometrical centre of X–ray emission). From the author's personal archive.

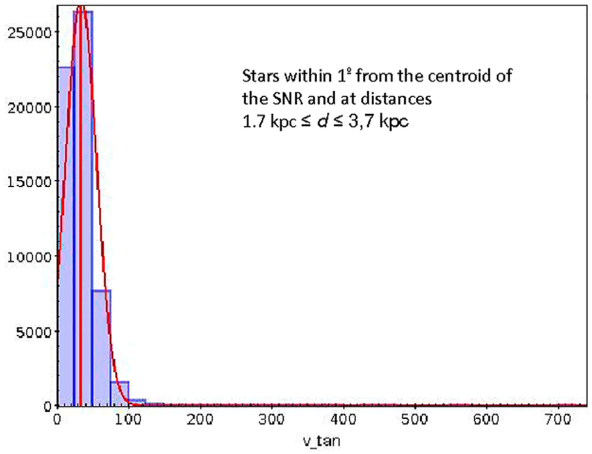

FIGURE 8
Histogram of the distribution of tangential velocities of the stars within 1 degree of the geometrical center of Tycho's SNR in the range of distance compatible with SN 1572 (1.7 < d < 3.7 kpc). The data are obtained from *Gaia DR3*. It can be seen that there are no hypervelocity stars in a very large area around the Tycho's SN remnant.

higher than the rest is Tycho G. The peculiarity of a star, Tycho G, comes from three facts: a larger proper motion mostly in declination than the other stars, a larger eccentricity and larger radial velocity in the LSR V_R (other star, Tycho U, has a similar proper motion in declination than Tycho G, but no eccentricity and a small V_R). No evidence for a high chemical pollution from the SN Ia is found in this only relatively peculiar star. It might be that this is what occurs for an impact on a main sequence or subgiant companion. It should be addressed as well if a star close to the explosion, but not being the companion, could be perturbed in the way Tycho G appears to have been. The single degenerate path to explosion has not been fully excluded for Tycho Brahe's supernova, from all the abovementioned factors.

From the theoretical work done on SN impacts on subgiants and on main sequence stars (see reviews in the previous paragraphs), the velocity of the companion and its pollution might not be very high. In the case of a donor star orbiting very close to the WD, though, one would expect an outlier at many more than 3σ of the proper motion distribution.

There have been some other observations pointing indirectly to a single degenerate origin rather than to a double degenerate origin for SN 1572. Zhou et al. (2016) have found that Tycho's SNR is surrounded by a clumpy molecular bubble, expanding at ~ 60 km s^{-1}. The bubble is massive and there is morphological correspondence with the SNR. The authors suggests that the origin of the expanding bubble is a fast outflow coming fron the vecinity of the mass-accreting WD that gave rise to SN 1572.

To complete this examination, we would like to see whether there are hypervelocity stars in the field of Tycho's SN remnant. The generous assumption of a 1 kpc distance to the remnant, 3,000 km s^{-1} and an age of 450 years, gives a search radius of 4.7 arcmin. No hypervelocity star is found. But, the whole field is totally empty of hypervelocity stars, even if we amplify the search to a 1 degree around the geomerical center of the remnant. For such radius and star distances between 1.7 and 3.7 kpc, the sample contains 58,691 stars (**Figure 8**). Thus we can exclude as an explosion mechanism for Tycho Brahe's SN the *dynamically driven double–degenerate, double–detonation scenario* D^6 mechanism (Shen et al. 2018). These explosions are triggered by the detonation of a surface layer made of He, accreted by the exploding WD from a less massive WD companion. The outburst might happen when the mass–donor has not yet been tidally disrupted. Due to its very high orbital velocity, the WD companion should be ejected as a hypervelocity star (v > 1,000 km s^{-1}). As we have seen, this is not the case for SN 1572.

In conclusion of this section, the explosion mechanism favored by the analysis of various authors suggests that a delayed detonation explains better the data than other possible alternatives. The single degenerate and the double degenerate scenario with a delay between merging and explosion fit into this picture. The new scrutiny using *Gaia DR3* of the stars in the field of SN 1572 gives a similar conclusion to that reached with the *Gaia DR2*. A few interesting notes and Figures can be found in he **Appendix**.

In the next decade, we expect to probe the nature of SNe Ia and quantify those coming from mergings of WDs with the new generation of gravitational wave missions in the deci-hertz range (see Yoshida (2020), for instance). We would be able to quantify the rates of SNe Ia coming through this path *versus* other origins. In the meanwhile, we have a battery of tests that are not so robust as a direct detection.

In the conclusions, I summarize the results gathered on the origin of the earliest SN Ia observed by astronomers.

5 Conclusion

We found in R04 that SN 1572 was a supernova very close to the template with a *stretch factor* s ~ 0.9. The light curve grows in precision towards the late times, being highly uncertain around maximum brightness. An overall agreement between early, late decline and color with the expected evolution of normal SNe Ia supports our conclusion.

Type Ia supernovae with *stretch factors* between 0.9 and 1.1 make the vast majority of the observed population. They are not only those most frequently found in nearby searches, but also the bulk of discoveries in cosmological searches at high–z, as can be seen in the sample of SNe at z > 0.3 found by the Supernova Cosmology Project (Perlmutter et al., 1999). Among SNe Ia of s ~ 0.9 in nearby galaxies for which very late–time data are available, we have found a close resemblance to SN 1996X in rate of decline. SN 1572 likely has a slightly slower rate. However, whereas SN 1996X was not heavily reddened, the reddening in SN 1572 is E (B–V) = 0.60 ± 0.05. The echo of SN 1572 discovered in 2008, reaffirms that SN 1572 is a normal SN Ia.

X-ray observations of Tycho's SNR have provided an increasingly detailed picture of the remnant and its surroundings. Although one-dimensional models do fit the overall charateristics of the SNR, three-dimensional simulations of its evolution, from the explosion to its current state, are being developed to account for the detailed structure.

Concerning the mechanism of explosion, a delayed detonation model seems to give a better account of the nucleosynthesis, as derived by various authors.

The possibility for a surviving companion has been throughly reexamined here with *Gaia DR3* data. The conclusion is similar to the one reached with the *Gaia DR2*.

Something seems clear from the exploration of the field of Tycho Brahe's supernova: the explosion is not triggered by the detonation of a surface layer made of He, accreted by the exploding WD from a less massive WD companion. Thus, it does not come from the so–called *dynamically driven double–degenerate, double–detonation scenario*. There are no hypervelocity stars in the field of SN 1572.

Finally, the merging of two WDs with a lapse between merging and explosion presents a possible path to this normal SN Ia: hydrodynamical calculations, which show that a delayed detonation in a near Chandrasekhar mass WD can occur in a double degenerate scenario where the explosion occurs with a delay after merging, change the view on the DD scenario. The delayed detonation of a Chandrasekhar WD had been for long investigated through the growth of the WD by accretion from a non-degenerate companion. But both paths seem possible for normal SNe Ia. Further exploration is needed to clarify the case of SN 1572.

Several aspects on Tycho Brahe's supernova are still unsolved 450 years after its visual detection. Being a normal SN Ia what can be learnt from this explosion, can help to understand the wide majority of supernovae of this type.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix

The most recent survey for a companion in Tycho Brahe's SN has been done so far using the *Gaia DR2* (Ruiz–Lapuente et al. 2019). With the recent *Gaia DR3*, we have examined whether those results are still valid. This is in fact the case: there are minor differences in the proper motions and parallaxes to the stars, but they do not affect the qualitative results. In **Table A1**, we display the differences for the stars that were used for the orbital calculations. In **Figure A9**, we present the new orbits of the stars. In **Figure A10** we show where Tycho G stands in proper motion in the field of stars 1 degree around the geometrical center of the SNR. It is very similar to what it was found with the *Gaia DR2*. In **Figure A11** we show how the sample stars used in previous Figures are located now in the *Gaia DR3*. Some stars have improved their parallax determination. But the overall picture is the same.

TABLE A1 Proper motions of stars *G, B, F* and *U*, in *Gaia* DR2 and DR3.

Star	μ_α^* (DR2) (mas yr^{-1})	μ_α^* (DR3) (mas yr^{-1})	μ_δ (DR2) (mas yr^{-1})	μ_δ (DR3) (mas yr^{-1})
G	-4.417 ± 0.191	-4.253 ± 0.093	-4.164 ± 0.143	-4.202 ± 0.097
B	-4.505 ± 0.063	-4.201 ± 0.030	-0.507 ± 0.049	-0.518 ± 0.031
F	-5.739 ± 0.130	-5.860 ± 0.054	-0.292 ± 0.097	-0.273 ± 0.058
U	-1.877 ± 0.113	-1.658 ± 0.054	-5.096 ± 0.083	-4.904 ± 0.057

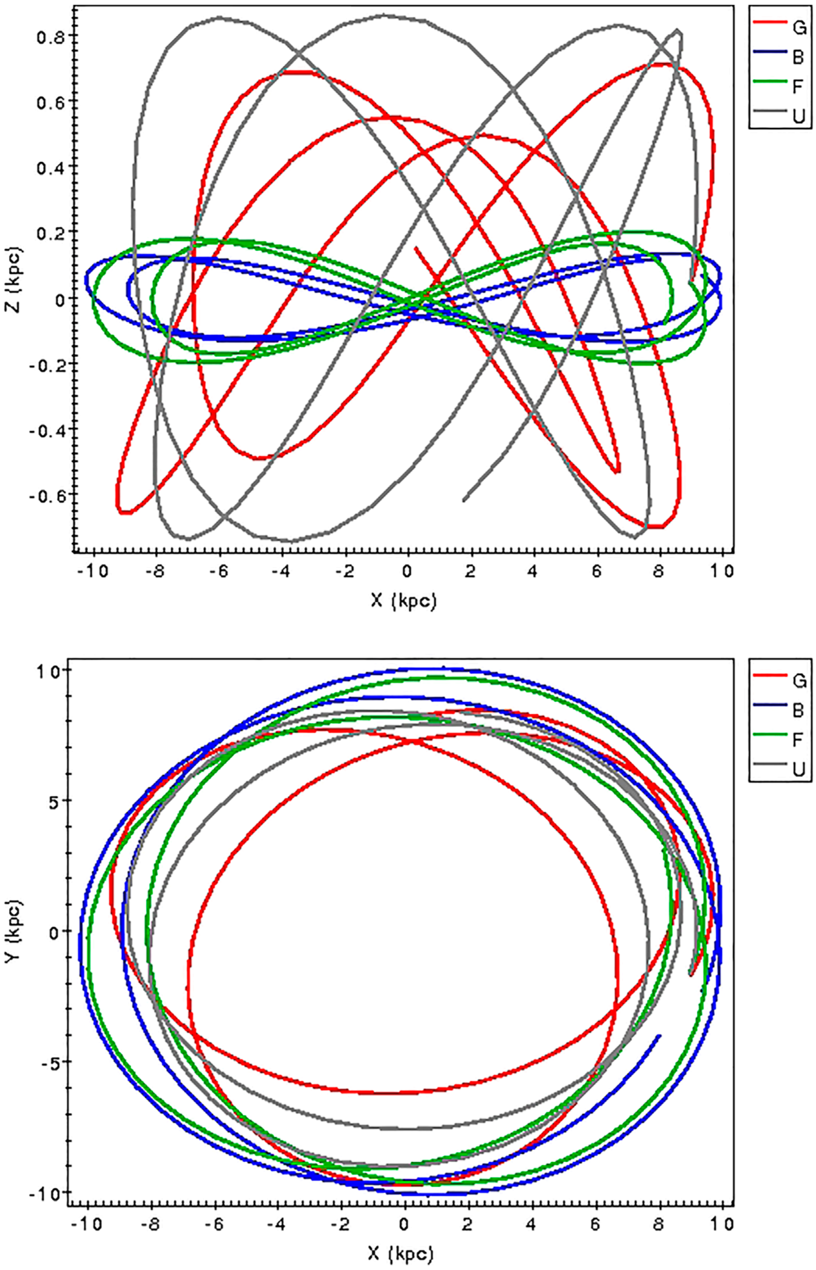

FIGURE A9
These Figures show the orbits of the stars with the new *Gaia DR3* proper motion data. There are no substantial changes compared to our 2019 exploration where we used the *Gaia DR2*. The orbits of stars B (blue), G (red), F (green) and U (gray), projected on the Galactic meridian plane (up) and on the Galactic plane (bottom), computed forward on time for the next 500 Myr. In the upper panel, we see that star U reaches the largest distance from the Galactic plane, followed by star G, while stars B and F scarcely depart from the plane. The behaviour of the latter stars is typical of the rest of the sample considered here. In the bottom panel, we see that the orbit of star G, on the Galactic plane, is quite eccentrical, which corresponds to the high value of the proper motion and V_R compared to the sample, while the other stars (including star U) have orbits close to circular. Also here, the behaviour of stars B and F is representative of the whole sample. Star E has a similar orbit than stars B and F.

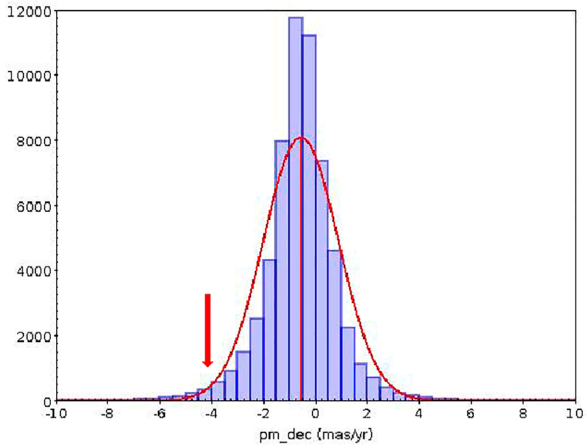

FIGURE A10
Histogram of the distribution in μ_δ (in mas yr^{-1}) of the stars within 1 degree of the geometrical center of Tycho's SNR in the range of distance compatible with SN 1572 (1.7 < d < 3.7 kpc). The data are obtained from *Gaia DR2*. The red vertical line shows the μ_δ of star G.

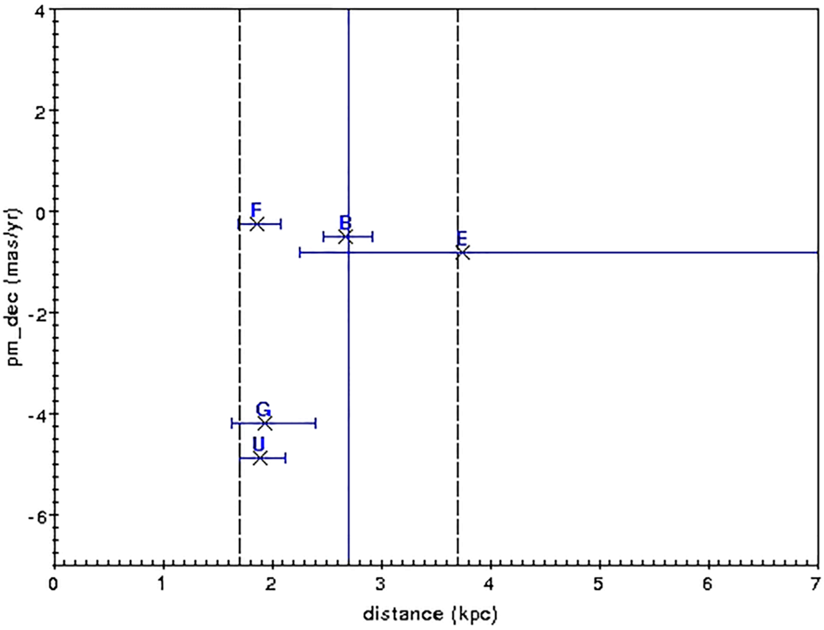

FIGURE A11
Distances and distance ranges inferred from the parallaxes in the *Gaia DR3* and their uncertainties, together with their proper motions in declination. The dashed vertical lines mark the conservative limits of 2.7 ± 1 kpc on the distance to Tycho's SNR. Solid (blue) error bars correspond to stars from **Table 1** that, within reasonable uncertainties, might be inside the SNR. See for more stars Ruiz–Lapuente et al. (2019), since results have not changed significantly.