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# TYCHO BRAHE'S SUPERNOVA: LIGHT FROM CENTURIES PAST

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## ABSTRACT

The light curve of SN 1572 is described in the terms used nowadays to characterize Type Ia supernovae (SNe Ia). By assembling the records of the observations done in 1572–1574 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 SN Ia family, the event should have been an SN Ia with a normal rate of decline, its stretch factor being $s \sim 0.9$. The visual light curve near maximum, late-time decline, and color evolution sustain this conclusion. After correcting for extinction, the luminosity of this supernova as observed at maximum is found to be $M_V = -19.24 - 5\log(D/3.0\ \mathrm{kpc}) \pm 0.42$. From stretch fitting of the overall light curve, the maximum in $V$ would imply a luminosity difference of $+0.17 \pm 0.1$ mag, with the maximum brightness of an $s = 1$ SN Ia. The quantity $M_V$ is consistent with a distance of $2.8 \pm 0.4$ kpc for the scale of $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$.


*Subject heading:* supernovae: general

## 1. INTRODUCTION

SN 1572 was well observed in Europe (as well as in the Far East) for almost 2 years. It added a new aspect to the debate at the time over Aristotelian cosmological views, as it forced the reconsideration of 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 only happened in the sublunar region. This was even the place where comets were assumed to originate. The appearance of SN 1572 challenged the order of the celestial spheres. The observers who followed it up[3] took sides with respect to established Aristotelian views. 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 observers billions of years 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 (SN I) came through the revision of the light curve done by Baade (1945) and based on data taken or quoted by Brahe (1603a). Before that time there was still speculation on whether it was a variable star of some kind or a nova (Morgan 1945), and even the suggestion of a cometary nature was still considered (Lynn 1883). The cometary idea expressed by Muñoz (1573) was based on the fact that the event was aligned with the Milky Way, so its decay in luminosity could be explained if it were a comet born among the stars that first approached and then moved away from us just along the line of sight. Tycho's *stella nova* lies indeed only 59–78 pc above the Galactic plane.

In modern times, its comparison with other supernovae allowed its classification as an SN I (Baade 1945). Later on, this class was shown to contain events of a very different nature: those identified with the explosion of white dwarfs (Type 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 Ic). SN 1572 was of the Type Ia class, as discussed by de Vaucouleurs (1985) and van den Bergh (1993). No further doubts that it is an SN Ia can now be held in view of the X-ray spectrum, which clearly differentiates SN Ia events from supernovae 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 us to think that it was fainter than normal SNe Ia. Van den Bergh (1993) considers whether it could be a peculiar, subluminous SN Ia, such as SN 1991bg. However, SN 1572 was heavily obscured. It was reddened by $E(B-V) = 0.6 \pm 0.04$, corresponding to the reddening of the stars near its position (Ruiz-Lapuente et al. 2003; P. Ruiz-Lapuente 2004a, in preparation). 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 an SN 1991bg–like event. Neither was it an overluminous SN Ia, such as SN 1991T or something similar, but rather an event in the middle of the SN Ia class.

## 2. NEW EVIDENCE ON VISUAL AND COLOR EVOLUTION AND LATE DECLINE

### 2.1. *Visual Light Curve until 60 Days*

The date of the maximum of SN 1572 is, from the available accounts, the most uncertain record. The first observation was done on November 6, although there is no record of the magnitude at that date (for a full discussion see Stephenson & Green 2002). On November 2 it was not yet noticeable, as reported by Muñoz (1573). On November 11, the date of the first observation done by Brahe (1603a) and the first reported observation by Muñoz (1573), it seems to have achieved a magnitude between those of Jupiter and Venus. The November 5 detection attributed to Muñoz as given in the *Progymnasmata* by Brahe (1603b) is an erroneous quotation, as we have verified in the original texts. November 11 is the date of the first recorded

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[3] The observers who mostly contributed to measuring 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 (P. Ruiz-Lapuente 2004b, in preparation).

observation in Spain. On November 16 and 17, when Caspar Peucer and Johannes Prätorius saw it, it seems to have had a magnitude close to that of Venus (Table 1 and notes). Later on, on January 7, it was already fainter than Jupiter (Muñoz 1573). The reconstruction of the observations suggests an apparent visual magnitude at maximum of $-4.0 \pm 0.3$ (Baade 1945; de Vaucouleurs 1985). The overall light curve fitting done in the present work by trying different decline rates (see below) indicates that the maximum was broad and that it should have taken place around November 21. On November 11, and even on November 16, when Peucer and Prätorius observed it, it would still have been on the rise. This is consistent with the mean rise time to maximum of SNe Ia, which in the $B$ band is $17.8^{+1.9}_{-1.0}$ days, as found in the high-$z$ SNe Ia sample of the Supernova Cosmology Project (Goldhaber et al. 2001), or $19.5 \pm 0.2$ days, as in the low-$z$ SNe Ia sample by Riess et al. (1999). The maximum in the $V$ band in SNe Ia occurs 2 days later than in the $B$ band. Riess et al. (1999) quote a fiducial rise time to $V$ maximum of $21.1 \pm 0.2$ days, i.e., 1.6 days longer than the $B$-band rise time. While most authors have arbitrarily taken November 15 as the date of visual maximum, it seems obvious that the maximum could not have happened before November 20: if we take the nondetection limit by Muñoz of 1572 November 2 and add 21 days, we would have a maximum around November 23. However, SNe Ia have a spread in the maximum luminosity of their light curves correlated with the rise time and the decline rate. The quoted 21 days of rise time is affected by a scatter of 1 $\sigma = 1$ day in the sample. Thus, a minimum rise time in the visual of 19 days (in the fast side of the distribution at 3 $\sigma$) gives November 21 as the earliest date of the visual maximum. In the following, we take November 21 as the reference date for the maximum. Since the naked-eye limit for that distance is deep as compared to the maximum brightness (9 mag below), the November 2 limit places constraints of 1–2 days on the date of the explosion.

The SN 1572 data are compared in this section with templates using the stretch factor $s$ as a characterization of the rate of decline (Perlmutter et al. 1999; Goldhaber et al. 2001; Nobili et al. 2003). The stretch factor $s$ method is used by the Supernova Cosmology Project to quantify the decline rate of supernovae from data extending up to 60 days after maximum. Even in the absence of a measurement of the brightness at maximum, the method allows one to produce a fine description of the supernovae within a family of decline rates. The magnitudes and limits on magnitudes for SN 1572, when compared with templates, lead us to conclude that this supernova was not fast. The best agreement found for SN 1572 corresponds to $s \sim 0.9$. In this regard, SN 1572 is very similar to SN 1996X, which had $s = 0.889$. A comparison can be seen in Figure 1, in which the data of SN 1572 are shown overplotted on an $s = 0.9$ SN Ia template in $V$. We also show for comparison the visual light curves of SN 1996X (a normal SN Ia of $s = 0.889$) and SN 1991bg (a fast subluminous event of $s = 0.62$). Therefore, these first 60 days show that there is no similarity with the fast, subluminous SN 1991bg. A broad light curve such as that of SN 1991T can also be excluded from the constraints on the decline (see Fig. 1).

### 2.2. *Late-Time Decline*

Additional proof that SN 1572 is a standard SN Ia comes from its slow late decline between 100 and 450 days after maximum, similar to that of the bulk of SNe Ia. SN 1572 had a late decline of 1.4 mag over 100 days during that epoch, in concordance with normal SNe Ia and far from the fast decline of SN 1991bg (Filippenko et al. 1992; Leibundgut et al. 1993; Ruiz-Lapuente et al. 1993; Turatto et al. 1996). SN 1990N and other normal SNe Ia had decline rates in such a period of 1.38–1.5 mag in 100 days. Consistent with the findings near maximum, the late time and overall similarity to the light curves of normal SNe Ia are found. In order to test the adequacy of the fit using the whole light curve, we construct new templates for a normal event of $s = 0.9$ (well exemplified by SN 1996X), a subluminous SN 1991bg–type event, and an overluminous SN 1991T–type event matching the available early- and late-time observations. Before 60 days those templates are equal to the Hamuy et al. (1996b) templates and the Supernova Cosmology Project templates for the corresponding stretches of those SNe Ia. At later times they follow the available late-time photometry (Schmidt et al. 1994; Salvo et al. 2001) to their latest available epoch. The fit of the SN 1572 data to the SN Ia template corresponding to $s = 0.9$ has a $\chi^2$ of 14.44 for 10 degrees of freedom, which is acceptable. In contrast, the fit to the template of a fast declining, underluminous SN Ia such as SN 1991bg ($s = 0.62$) has an exceedingly high $\chi^2$ of 53.55 for 4 degrees of freedom (the two premaximum points, as well as the last four points, have been excluded because of the lack of data for subluminous SNe Ia at such a stage). At the other end, the fit to the template of a slow-declining, overluminous SN Ia such as SN 1991T ($s = 1.2$) is almost as bad, with a $\chi^2$ of 82.99 for 10 degrees of freedom.

In Figure 2 we show the overall visual light curve until almost 500 days compared with that of SN 1996X and the templates for SN 1991bg and SN 1991T. The last upper limit given by Tycho Brahe indicates that at 480 days past maximum, the supernova had not yet leveled off from light echoes produced in the intervening dust clouds. Not all the SNe Ia in dusty regions have shown light echoes associated with the scattering of the supernova light in neighboring dust clouds, however. The production of light echoes depends on the spatial distribution of dust relative to both observer and supernova. In the case of SN 1986G, a very heavily reddened supernova, such a light echo was not observed (Schmidt et al. 1994). However, for SN 1572 one cannot exclude a leveling off occurring later, at a fainter magnitude level. SN 1991T and SN 1998bu have indeed shown a slowing down of the $V$-magnitude decline at around 400 days as result of the light echo (Schmidt et al. 1994; Cappellaro et al. 2001), and the leveling off occurs at 500 days, about 10 mag below the maximum brightness. For SN 1572 an equivalent step in the level of brightness would correspond to $V = 6$, which is about the naked-eye limit. SN 1998bu is an SN Ia very similar to SN 1996X and SN 1572 but with a reddening of $E(B - V) = 0.32 \pm 0.04$ (Hernandez et al. 2000; Cappellaro et al. 2001). Tycho Brahe's supernova would be like SN 1998bu with twice the reddening.

Moreover, the late-time decline of SN 1572 informs us of the deposition of energy from the decay $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ in the ejecta of this supernova. Its slow decline would fit the declines predicted for SNe Ia coming from the explosion of Chandrasekhar-mass white dwarfs. The late-time decline in $V$ indicates a significant deposition of energy from positrons, which arise in the decay $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$. At 200 days after the explosion, positrons become the dominant source of luminosity. Departures from full trapping of $^{56}$Co decay are seen in all SNe Ia, as expected. They arise from the lack of confinement of positrons to the ejecta of the supernova and/or incomplete thermalization

TABLE 1

VISUAL ESTIMATES OF TYCHO'S SUPERNOVA

| Date | Day | Phase Adopted | Description | $m_V$ | Notes |
|---|---|---|---|---|---|
| 1572 Nov 2 | Nov 2 | ... | No detection | >5 | [1] |
| 1572 Nov | Nov 11 | −10 | Somewhat brighter than Jupiter and almost equal to the Morning Star | −3 ± 0.3 | [2] |
| 1572 Nov | Nov 11 | −10 | Equaled Venus when this planet was at maximum brightness | −3.2 ± 0.3 | [3] |
| 1572 Nov 16, 17 | Nov 16 ± 1 | −5 ± 1 | Almost as bright as Venus and Jupiter | −4.0 ± 0.3 | [4] |
| 1572 Dec | Dec 15 ± 7 | 24 ± 7 | About as bright as Jupiter | −2.4 ± 0.3 | [5] |
| 1573 Jan 7 | Jan 7 | 47 | Already fainter than Jupiter | >−2 | [6] |
| 1573 Jan | Jan 15 ± 7 | 55 ± 7 | A little fainter than Jupiter and brighter than the brighter stars of first magnitude | −1.4 ± 0.4 | [7] |
| 1573 Feb–Mar | Mar 2 ± 14 | 101 ± 14 | Equal to brighter stars of first magnitude | +0.3 ± 0.2 | [8] |
| 1573 Apr–May | May 1 ± 14 | 161 ± 14 | Equal to stars of second magnitude | +1.6 ± 0.5 | [9] |
| 1573 July–Aug | Aug 1 ± 14 | 253 ± 14 | Equal to $\alpha$, $\beta$, $\gamma$, $\delta$ Cas | +2.5 ± 0.2 | [10] |
| 1573 Oct–Nov | Nov 1 ± 14 | 345 ± 14 | Equal to stars of fourth magnitude (among Cassiopea stars) | +4.0 ± 0.2 | [11] |
| 1573 Nov | Nov 15 ± 7 | 359 ± 7 | Equal to $\kappa$ Cas | +4.2 ± 0.2 | [12] |
| 1573 Dec–1574 Jan | Jan 1 ± 14 | 406 ± 14 | Hardly exceeding stars of fifth magnitude | +4.7 ± 0.2 | [13] |
| 1574 Feb | Feb 15 ± 7 | 451 ± 7 | Equal to stars of sixth magnitude | +5.3 ± 0.4 | [13] |
| 1574 Mar | Mar 15 ± 7 | 479 ± 7 | Invisible | >6 | [14] |

[1] Jerónimo Muñoz writes that he was certain that on 1572 November 2, the "comet" was not in the sky, as he was "teaching knowledge of the stars to a numerous group of people that evening" (Muñoz 1573). Jerónimo Muñoz (?–1592) was professor of Hebrew and Mathematics at the University of Valencia and later on of Astrology at the University of Salamanca. The records assembled here are from his *Libro del nuevo cometa* [Book of the New Comet], written as King Philip II consulted him on SN 1572. He determines the absence of parallax of the star and gives estimates of color and magnitude, although his account is mostly addressed to the criticism of Aristotelian cosmology. He writes that the heavens and stars are not made of quintessence but related to the elements and advocates the reconsideration of the pre-Socratic cosmological views of Democritus and Anaxagoras. Brahe (1603b) compiled parts of Muñoz's observations and discussed those views in the third volume of the *Progymnasmata*. He left out, however, some useful information that we have added here. We also corrected the premaximum quote.

[2] November 11 is the first observation quoted by Muñoz in his book. The apparent magnitude appeared "somewhat greater than that of Jupiter, which was 59 degrees distant from the comet, and almost equal to that of the Morning Star." Jupiter was at that time $V = -2.61$, and Venus $V = -4.35$ (Baade 1945). We assign $-3.0 \pm 0.3$.

[3] On November 11 Tycho Brahe also saw the supernova, and his preliminary report in *De nova stella* said that it "equaled Venus when this planet was at maximum brightness." He was, however, more conservative in the account he gives in the *Progymnasmata*. We give −3.2 mag to the estimate of Tycho ±0.3. In the following we must keep in mind that Tycho Brahe observed from a latitude of ∼N55°, as he stayed in the area of Copenhagen for 2 years after the discovery of SN 1572. From that location the supernova could be observed well above the horizon through the whole year. De Vaucouleurs (1985) notes that when comparing SN 1572 with Venus, one has to account for the fact that the former was not affected by extinction, while the latter was significantly affected. This indicates $V = -3.8$ or fainter if one considers the apparent magnitude of Venus affected by extinction.

[4] Tycho Brahe reports in the *Progymnasmata* on the observations done by Caspar Peucer and Johannes Prätorious on November 16. According to the former, "it surpassed in brightness all stars and planets with the exception of Venus," and according to the latter, it was "brighter than Jupiter but easily fainter than Venus." Michael Mästlin, who saw it before November 17, states that it "almost equaled Venus." These estimates have been given a value of $V = -4.0 \pm 0.3$.

[5] Tycho Brahe does not give the exact date of the observations. He quotes the month or an interval encompassing 2 months. It is reasonable to think that he refers to dates in the middle of the period. Therefore, we follow here Baade (1945) and assign the middle of the period as the date of observation. However, we add ±7 days of uncertainty in the case in which a month is quoted and ±14 days if the period encompasses 2 months.

[6] This is an upper limit given by Muñoz. He writes, "when it began to be visible, it looked larger than Jupiter, and now, on January 7, 1573, it already looks smaller than Jupiter; this could have happened because it had risen higher than where it was when it first appeared." This upper limit to the rate of decline, as well as the data around this date obtained by Tycho Brahe, constrains the light curve stretch factor to below $s = 1.1$.

[7] This is a difficult estimate. The interval quoted encompasses 2.46 mag (see Baade 1945). The interpolation is uncertain, from Jupiter with $V = -2.18$ to the brightest stars of the first class, which are +0.28. We assign to the Baade estimate of $V = -1.4$ an uncertainty of ±0.4.

[8] This a slightly better estimate, as it encompasses a smaller range in magnitude, ±0.2, if one selects the brighter range of first-magnitude stars (0.2–0.3).

[9] This is a very ambiguous quote; one should assign it an uncertainty of ±0.5. The stars of second magnitude had a range encompassing 1 mag, $m_V = 4.0$ and $\sigma_V = 0.5$. This is the point that lies far from the expected curve. We have checked whether a problem of differential extinction could have affected SN 1572 with respect to the second-magnitude stars, but there were second-magnitude stars at altitudes similar to SN 1572. The offset of 0.6 mag cannot be attributed to extinction problems but can be attributed to the ambiguous description of the record.

[10] Tycho Brahe's estimates in magnitude are more precise now, as he refers to particular stars not far from the supernova with a low scatter in magnitude. The mean of those stars is $m_V = 2.48$, and $\sigma_V = 0.23$. We assign ±0.2 to the error in the magnitudes of those stars.

[11] This becomes a very precise estimate by comparing with the fourth-magnitude stars in Cassiopeia, when knowing that the supernova was brighter than the nearby eleventh star of Cassiopeia. An error of 0.2 mag is assigned.

[12] This seems to be the most precise description, as it says the supernova is equal to $\kappa$ Cas.

[13] Errors of 0.2 and 0.4 mag, respectively, seem reasonable for these last estimates.

[14] It can be noted that the quote that the supernova was not observable later than 1574 March ($V > 6.0$) allows us to exclude the possibility that the luminosity leveled off, based on a light echo at ∼10 mag below the supernova maximum brightness.

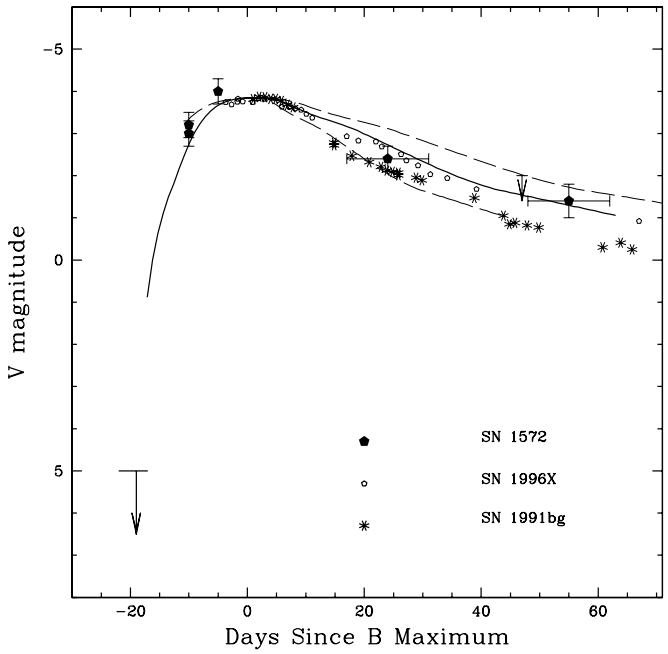



FIG. 1.—Visual light curve of SN 1572 until 60 days. The solid curve shows the $V$ light curve of an $s = 0.9$ SN Ia, which gives the best account for the decline. Such a stretch factor is typical of normal SNe Ia. We show for comparison the $V$ light curve of the normal SN Ia 1996X, whose stretch factor 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 SN 1991bg–type events and SN 1991T–like events, which depart significantly from the data.

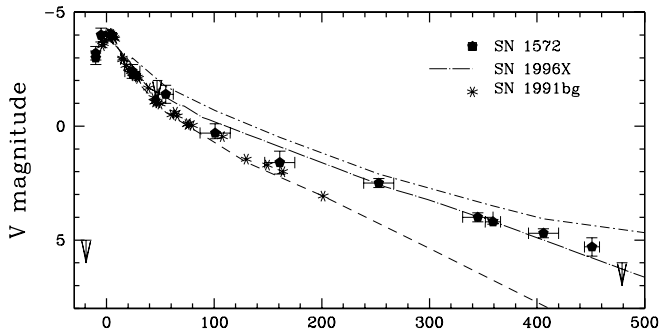



FIG. 2.—Visual light curve of SN 1572 until 500 days. Its late rate of decline is one of a normal SN Ia. It is very similar to the decline of the $s = 0.889$ SN 1996X. The visual data of SN 1991bg and the template light curves of this SN Ia and SN 1991T are shown for comparison.

of their energies. Various effects can lead to diversity in late-time supernova bolometric light curves: nucleosynthesis, kinematic differences, ejected mass, the degree of mixing of the ejecta, and the configuration and intensity of the magnetic field. In particular, as suggested in Ruiz-Lapuente & Spruit (1998), those late-time declines can be used to investigate the magnetic field configuration of the supernova and trace it back to the original configuration in the white dwarf right before explosion. It is found that departures from the full trapping of $^{56}$Co decay on the order of 10%–15% at about 400 days can be explained by the distribution of radioactive material. Larger departures, of 30%–40% or more, have to be interpreted in terms of the lack of the magnetic field confinement of positrons or even the enhancement of escape caused by a radially aligned configuration of the magnetic field. In the case of SN 1991bg the very fast drop of the late light curve suggests not only a total ejected mass well below the Chandrasekhar mass but an absence of a significant tangled magnetic field as well. An exploration of the late-time decline predicted for different explosion models compared with a sizeable sample of bolometric light curves was done by Milne et al. (1999). For SN 1572, the availability of data is limited to the visual band. However, analogies can be drawn with similar SNe Ia for which the bolometric data are available.

Core-collapse supernovae (of Type II or Type Ib/Ic) differ both in the early light curve (before 60 days) and in the late-time decline (after 60 days) from SNe Ia. For those core-collapse supernovae for which the late-time decline is observed, the rate is slower than for Type Ia, as there is a larger mass ejected in the explosion, and the optical depth for $\gamma$-rays is larger (see, e.g., Ruiz-Lapuente 1997; Cappellaro & Turatto 2001). Even for those supernovae of Type Ic relatively similar in brightness at maximum to SNe Ia (Clocchiatti et al. 2000), the late-time decline is closer to Type II, and the overall light curve can be clearly distinguished from SNe Ia.

To summarize this section, the late-time decline, in addition to showing that SN 1572 is an SN Ia, gives major proof confirming that this historical supernova is not part of the estimated 16% of intrinsically subluminous SNe Ia (Li et al. 2001), likely arising from a different class of explosion ejecting a smaller amount of mass (Ruiz-Lapuente et al. 1993). If it were part of the class of peculiar subluminous SNe Ia, caution should be given when using it for cosmology, because it is not clear whether those subluminous events are in a linear relation of brightness to rate of decline.

### 2.3. *Reddening and Color*

The most direct estimate of the reddening comes from our measurement of the reddening and extinction of the stars around the geometric center of SN 1572 at the distance of the supernova (Ruiz-Lapuente et al. 2003; P. Ruiz-Lapuente 2004a, in preparation). The stars that are compatible with a distance in the range of $3 \pm 1$ kpc (see de Vaucouleurs 1985 for a review of the distances toward SN 1572) have reddenings that average to $E(B - V) = 0.6 \pm 0.04$. Those values were derived from the search for companion stars of Galactic SNe Ia (Ruiz-Lapuente et al. 2003; P. Ruiz-Lapuente 2004a, in preparation). Star candidates for the companion of SN 1572 are modeled to determine $T_{\rm eff}$, $\log g$, metallicity, distance, and $E(B - V)$. In this way, a reddening is obtained for the stars within a circle encompassing the innermost 12% of the Tycho supernova remnant (SNR) around the geometric center of the X-ray emission.

The above mean reddening to SN 1572 corresponds to an extinction $A_V = 1.86 \pm 0.12$ mag if we take $R_V = 3.1$ (Sneden et al. 1978; Rieke & Lebofsky 1985). The Galactic extinction data based on *COBE* DIRBE observations (Drimmel & Spergel 2001) give a value of $A_V = 1.77$ mag in that direction (the maximum Galactic extinction being $A_V = 1.90$ mag there). Thus, the extinction measured at the distance of SN 1572 is in agreement with the *COBE* results. Correcting the apparent brightness from the dimming by dust, we find again that Tycho's supernova was not subluminous but a normal SN Ia.

We can correct as well the color of the supernova from the records of the epoch and derive the intrinsic color evolution. SNe Ia are found to show a similar color evolution 2 months after maximum, with a well-established law of low intrinsic

TABLE 2
COLORS OF TYCHO'S SUPERNOVA

| Date | Day | Phase Adopted | Description | $B - V$ Adopted | Notes |
|---|---|---|---|---|---|
| 1572 Nov ..... | Nov 21 ± 7 | −6 ± 7 | Like Venus ($B - V = 0.83$) and Jupiter ($B - V = 0.82$) | 0.82 ± 0.25 | [1] |
| 1572 Dec..... | Dec 1 ± 5 | 10 ± 5 | Yellowish | 1.0 ± 0.25 | [2] |
| 1572 Nov–Dec ..... | Dec $2^{+7}_{-22}$ | $11^{+7}_{-22}$ | Between Saturn ($B - V = 1.04$) and Mars ($B - V = 1.36$), closer to Mars | 1.2 ± 0.25 | [3] |
| 1572 Jan..... | Jan 1 ± 7 | 41 ± 7 | Like Aldebaran ($B - V = 1.52$) | 1.52 ± 0.25 | [4] |
| 1573 Jan..... | Jan 15 ± 7 | 55 ± 7 | Similar to Mars ($B - V = 1.36$) | 1.36 ± 0.2 | [5] |
| 1573 Feb ..... | Feb 28 ± 7 | 99 ± 7 | Return to original | 0.82 ± 0.25 | [6] |
| 1573 May..... | May 15 ± 7 | 175 ± 7 | Like the original ($B - V = 0.83$) | 0.82 ± 0.25 | [7] |

[1] Various reports (see Baade 1945) give a color similar to the colors of Venus and Jupiter.
[2] Brahe (1603a) states that after maximum the supernova became yellowish in color. By comparison with the descriptions of being whitish (like Jupiter) and red (like Aldebaran), we assign $B - V = 1.0 \pm 0.25$.
[3] Muñoz (1573) states that the color was between those of Saturn and Mars, and closer to Mars. One could then identify the color as $1.2 \pm 0.25$. Unfortunately, there is ambiguity in the date he is referring to; he mentions that he first saw it on December 2 and checked with observers that it was already there on November 11. He uses the expression "the color then was," so it is not clear whether he refers to November 11 or December 2. It seems that the description, because of its detail, is based on his own appreciation of the color on December 2 (we place an error bar in the dates toward November 11 and a 7 day error after December 2).
[4] Tycho Brahe notes that shortly after the beginning of the year, the supernova was red like Aldebaran (Brahe 1603a). We assign 0.25 mag of uncertainty to those estimates.
[5] According to Prätorius, the supernova was like Mars for 2 months after its appearance (around January 15).
[6] Mästlin states that at the end of February, the supernova was going back to its whitish color. Tycho states that it had a red color during February and March, becoming whitish after May. However, this seems to be a worse account of the color than the one given by Mästlin. In April the supernova is described as silverish by some observers in Spain and as being similar to Saturn (van den Bergh 1970).
[7] The last estimate is given as $0.82 \pm 0.25$ in the account by Tycho Brahe on the color in May.

dispersion valid from 30 to 90 days, as explored in Phillips et al. (1999, hereafter Ph99) based on the work of Lira (1995):

$$(B - V)_0 = 0.725(\pm 0.05) - 0.0118(t_V - 60), \qquad (1)$$

where $t_V$ is the time since visual maximum.

The color of SN 1572 2 months after discovery was reported to be similar to those of Mars and Aldebaran (thus, with $B - V$ in the range 1.36–1.54). Previous and subsequent color estimates are also shown in Table 2. After correcting the observed color by our measurement of reddening, $E(B - V) = 0.6 \pm 0.04$, the intrinsic color at $55 \pm 10$ days is $(B - V)_0 = 0.76 \pm 0.24$, very much in agreement with the expected $(B - V)_0 = 0.78 \pm 0.15$ for that epoch. Such color fits very well in the Ph99 law for the time evolution of the intrinsic color of SNe Ia. In agreement with that law, Nobili et al. (2003) have shown that the color evolution of the bulk of SNe Ia has a low dispersion of 0.1 mag in the tail. Before maximum the corrected color of SN 1572 would be $(B - V)_0 = 0.22 \pm 0.29$, thus consistent with the fact that normal SNe Ia have $(B - V)_0 \sim 0$. SN 1991bg and other subluminous SNe Ia clearly deviate from the standard color evolution at early epochs, being intrinsically red at maximum, $(B - V)_0 = 0.6$ (Leibundgut et al. 1993; Ph99). Moreover, the color evolution derived from the $B$ and $V$ templates for an $s = 0.9$ SN Ia has good agreement with the observed values in this supernova. In Figure 3 we show the color light curve of SN 1572, corrected by $E(B - V) = 0.6$, compared with that of normal SNe Ia. Both the peculiar SN 1991bg and the normal SN 1996X are also shown in their reddening-corrected colors.

The data displayed in this figure come from different observers (see Table 2 and notes). Color estimates by eye are made more difficult by the lack of an established system that encompasses the whole range of colors. The conversion of eye-estimated colors to our filter scale is addressed in Pskovskii (1977) and Schaefer (1996). To add to the inherent uncertainty in estimating color by eye, it has to be noted that the first comparisons done by the observers of the time using planets such as Jupiter, Venus, or Saturn as references were made more difficult by the fact that the planets were often very far from the position of SN 1572 (apart in the sky by 59°). De Vaucouleurs (1985) discussed the effect of that on the early visual estimates (later estimates, since they are done through comparison with particular stars, are more reliable).

In the nebular phase, at 175 days according to Tycho Brahe's records (Table 2), the supernova went back to a white color, which is consistent, after correcting for reddening, with what is found in normal SNe Ia as well. Uncertainties in the color estimates have been assigned, and new records included.

### 2.4. *The Luminosity of Tycho's Supernova*

Given the apparent visual magnitude, the luminosity of Tycho Brahe's supernova would have corresponded to an absolute visual magnitude of

$$M_V = -17.38 - 5 \log (d/3.0 \text{ kpc}) - A_V. \qquad (2)$$

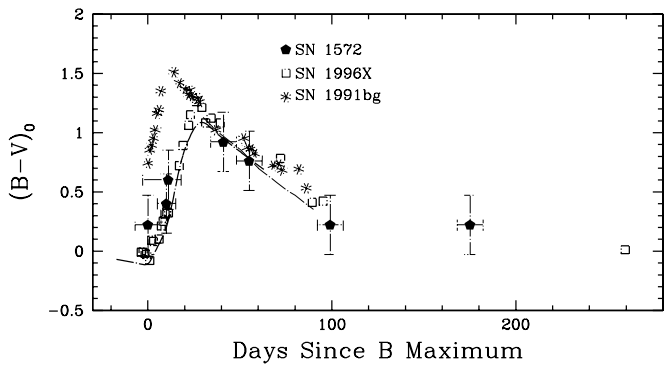



FIG. 3.—Color evolution of SN 1572 corrected from extinction as compared with normal SNe Ia and SN 1991bg. SN 1572 is consistent with the color evolution of an $s = 0.9$ SN Ia (the template for this stretch is plotted as the dot-dashed curve). SN 1996X has been corrected for its very small reddening $E(B - V) = 0.01 \pm 0.02$, as well as SN 1991bg [$E(B - V) = 0.03 \pm 0.05$] (Ph99).

If corrected for $A_V = 1.86 \pm 0.12$, this gives

$$M_V = -19.24 - 5 \log (d/3.0 \text{ kpc}) \pm 0.42. \quad (3)$$

De Vaucouleurs (1985) gives the most likely estimate of the distance to SN 1572 as $3.2 \pm 0.3$ kpc. Taking 3.2 kpc for the distance, the luminosity would be $-19.38 \pm 0.42$. That can be compared with the value $M_V = -19.12 \pm 0.26$, the mean magnitude from the Calán/Tololo sample referring to $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ (Hamuy et al. 1996a). In his review of distances, de Vaucouleurs gives a mean estimate taken from various approaches while mentioning the assumptions made in these methods. New distance estimates have appeared since then, still pointing to the same range, i.e., 2–4 kpc. Albinson et al. (1986) argue in favor of a distance to SN 1572 of $2.2^{+1.5}_{-0.5}$ kpc from two approaches: from the distance determined photometrically to Population I objects near the supernova location and from the interpretation of neutral hydrogen absorption toward the remnant using Galactic rotation curve models. These authors find that the absorption and emission profiles of H I indicate that the radio remnant of Tycho (3C 10) is embedded in the near side of the gaseous part of the Perseus spiral arm. Schwarz et al. (1995) find, however, that the velocity-distance relation with H I features cannot be interpreted easily with nonlinear density wave rotation models. They derive that the distance to SN 1572 can be as large as 4.5 kpc.

It is possible to obtain a more refined distance to SN 1572, using the SNR expanding parallax method (Kirshner et al. 1987) with precise measurements of the proper motion of the filaments ($\mu$) and narrow estimates of the shock velocity ($v_{\rm sh}$) of the expanding remnant. The shock wave results from the interaction of the supernova ejecta with the interstellar medium, mostly made of hydrogen atoms. The interstellar material is overrun to significant velocities and radiates in H$\alpha$. A determination of the forward shock movement and a reliable measurement of the proper motion of the material near the shock leads to a distance measurement as $d \propto v_{\rm sh}/\mu$. Spectra along different sectors of the SNR are required to evaluate the range of shock velocity values and proper motions. In Winkler et al. (2003) a distance to SN 1006 of $2.18 \pm 0.08$ kpc was obtained through this approach.

The proper motion of the filaments in SN 1572 was measured by Kamper & van den Bergh (1978), and it is about $0\farcs22 \pm 0\farcs02$ yr$^{-1}$. There is, however, a larger uncertainty in the estimate of the shock velocity, which is obtained through modeling of the broad H$\alpha$ emission of the material swept up by the supernova. This estimate is model dependent and improves with a better knowledge of the composition and physical state of the fully ionized plasma behind the shock. Kirshner et al. (1987) had suggested from the observations available at that time a distance to SN 1006 of 1.4–2.1 kpc and a distance to SN 1572 of 2.0–2.8 kpc. The estimates of the shock velocity, however, are being revised from the wealth of spectral observations of the SN 1572 filaments taken during the last years. From the latest estimates, one finds $v_{\rm sh} = 2500 \pm 500$ km s$^{-1}$ as a mean of the values obtained by Smith et al. (1991) and Ghavamian et al. (2001). The error, of 20%, is associated with modeling assumptions and asymmetries in $v_{\rm sh}$.

An estimate of the distance to Tycho's supernova can be made by comparison of the angular diameters of the two historical SNe Ia. The angular diameter of G327.6+14.6 (the remnant of SN 1006) is $\theta(1006) = 30\farcm60 \pm 0\farcm06$, whereas that of Tycho is $\theta(\text{Tycho}) = 8\farcm65 \pm 0\farcm05$. We can place

$$\frac{\theta(\text{Tycho})}{\theta(1006)} = \frac{d(1006)}{d(\text{Tycho})} \frac{\Delta t(\text{Tycho})}{\Delta t(1006)} \eta, \quad (4)$$

where $\Delta t$(Tycho) and $\Delta t$(1006) are the respective ages of the remnants and

$$\eta = \frac{v(\text{Tycho})}{v(1006)} \frac{[1 - (1/2)(1 - \nu)_{\rm Ty}]}{[1 - (1/2)(1 - \nu)_{1006}]} \quad (5)$$

is the ratio of the average expansion velocities of the two supernova ejecta taking into account up to first order in $t$ the deceleration of the shock front. We use, for the deceleration of the front, a value assuming that the radius of the shock moves as $R_{\rm sh} \propto t^{\nu}$, where $\nu$ is the expansion index of the SNR. Then, $\dot{v}_{\rm sh} = -v_{\rm sh}(1 - \nu)t^{-1}$ and $R_{\rm sh} \sim v_{\rm sh}[1 - \frac{1}{2}(1 - \nu)]\Delta t$. We take the distance obtained by Winkler et al. (2003) to SN 1006 of $2.18 \pm 0.08$ kpc, the shock velocity for SN 1006 of $2890 \pm 100$ km s$^{-1}$ used in that work, and the expansion index for this SN Ia of $\nu = 0.48 \pm 0.13$. For SN 1572 the less precise $v_{\rm sh} = 2500 \pm 500$ km s$^{-1}$ (see above) and $\nu = 0.45 \pm 0.5$ are used. The derived distance is then $d_{\rm Tycho} = 2.83 \pm 0.79$ kpc. As different shock velocities have been inferred from various knots of the nebula of Tycho, further sampling of the expansion in several directions should be done to improve the use of this approach. The irregularities of the ambient medium (Hamilton et al. 1986) and the presupernova history (Badenes & Bravo 2001) give rise to a complexity in the evolution of the expanding remnant beyond an idealized symmetrical solution. However, the expansion distance can be very much improved through observations.

The above shows that, at present, it is difficult to escape from the uncertain range in the distance to SN 1572 with the analyses done so far. Such a limitation does not prevent us from inferring the right place of SN 1572 within the luminosity sample: the conclusion on the brightness rate of decline for SN 1572 is based on the gathered empirical evidence and the well-established use of the peak luminosity–decline correlation. Within the sample, such an $s = 0.9 \pm 0.05$ SN Ia would imply a luminosity difference from an $s = 1$ SN Ia of $+0.17 \pm 0.1$ mag. For $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, the calibration of SNe Ia within the family of events using the stretch-calibrated fit would imply a distance of $2.85 \pm 0.4$ kpc and an absolute $V$-magnitude of $M_V = -18.95 \pm 0.2$.

From a well-derived distance to SN 1572, one could obtain the distance to SN 1996X, which is not well determined with the present available methods. The $D_n$-$\sigma$ relation gives a distance modulus $\mu = 31.32 \pm 0.4$ (Faber et al. 1989), whereas the SNe Ia calibration using $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ would place it at a significantly larger distance (Salvo et al. 2001). The very good agreement between the late-time light curves of SN 1572 and SN 1996X allows us to infer a $\Delta\mu$(SN 1572 − SN 1996X) = $18.9 \pm 0.12$ between the two SNe Ia.

## 3. CONCLUSIONS

We have found that SN 1572 was a supernova very close to the template with a stretch factor $s \sim 0.9$ (see Table 3 for a summary). The light curve grows in precision toward late times, being highly uncertain around maximum brightness. An overall agreement between early brightness and late decline and color with the expected evolution of normal SNe Ia supports our conclusion.

TABLE 3
SN 1572

| Parameter | $s$ | $\Delta m(V)_{20}$ | $\Delta m(V)_{60}$ | $\gamma_{(V)}^{\rm late}$ | $B - V_0$ |
|---|---|---|---|---|---|
| SN 1572..... | $0.9 \pm 0.05$ | $1.1 \pm 0.4$ | $2.6 \pm 0.6$ | $1.6 \pm 0.04$ | $0.22 \pm 0.25$ |
| SN 1991bg–like..... | 0.62 | 1.68 | 3.3 | 2.7 | 0.6 |
| SN 1991T–like..... | 1.2 | 0.72 | 2.46 | 1.68 | −0.1 |
| Normal[a]..... | 0.9 | 0.9 | 2.8 | 1.7 | 0.0 |

[a] Normal SNe Ia of $s = 0.9$. Whereas the $\Delta m(V)_{20}$ is not well defined for SN 1572 because of a lack of accurate observations in the week around the maximum, the rate of decline in terms of stretch can be well determined by fitting premaximum and postmaximum up to 60 days.

SNe Ia with stretch factors between 0.9 and 1.1 make up 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 supernovae at $z > 0.3$ found by the Supernova Cosmology Project (Perlmutter et al. 1999). Among SNe Ia of $s \sim 0.9$ in nearby galaxies for which very late-time data are available, we have found a close resemblance to SN 1996X in the 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 $E(B - V) = 0.60 \pm 0.05$. While at present heavily reddened SNe Ia present more difficulty than unreddened ones for proper use in cosmology (Riess et al. 2000; Knop et al. 2003), a better use of multicolor light curves should allow us to overcome the problem.

Tycho Brahe's supernova belongs to the Ia type, which is used for the determination of the nature of dark energy. Its light, already traveling away from us toward places light years away, carries information on our epoch of acceleration to an even more dark energy–dominated future. If used for cosmology by observers in galaxies billions of light years distant, it would require, certainly, a careful handling of its intrinsic brightness.

This paper, among others to come, is dedicated to my father, Professor C. Ruiz Ogara. Past, present, and future merged for him just a few months ago, as sadly as unexpectedly. His life was devoted to helping the souls of many and to furthering research in brain and mind studies. His inner light lives forever with us. I would like to express my gratitude to M. A. Granada, from the Department of History of Philosophy of the University of Barcelona, for helping to locate the sixteenth-century historical sources.

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