



The Light Curve and Distance of the Kepler Supernova: News from Four Centuries Ago

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Abstract

We study the light curve of SN 1604 using the historical data collected at the time of observation of the outburst. Comparing the supernova with recent SNe Ia of various rates of decline after maximum light, we find that this event looks like a normal SN Ia (stretch s close to 0.9 : 0.9 ± 0.13), a fact that is also favored by the late light curve. The supernova is heavily obscured by 2.7 ± 0.1 mag in V . We obtain an estimate of the distance to the explosion with a value of $d = 5 \pm 0.7$ kpc. This can help to settle ongoing discussions on the distance to the supernova. It also shows that this supernova is of the same kind as those of the SN Ia samples that we now use for cosmology.

Key words: distance scale – supernovae: general – supernovae: individual (SN 1604)

1. Introduction

The supernova of 1604 was observed by Johannes Kepler and other astronomers in Europe, Korea, and China. Not so many years before, the supernova SN 1572, currently named Tycho's supernova, was the subject of extensive studies, both astronomical and philosophical, by Tycho Brahe (Brahe 1603).

The supernova in 1604 also inspired observational measurements and philosophical considerations by Kepler. The philosophical disquisitions were on the nature of the heavens. The idea of crystal spheres carrying planets and rolling over one another had already been shattered by the discovery of SN 1572. The possibility of a heaven that gives birth to natural objects emerged in the following years, and was enhanced by the discovery of the supernova of 1604. Kepler wrote his reflections in a book called *De Stella Nova in Pede Serpentariis* (1606). The collection of his observational records on SN 1604 and those of his colleagues are found mostly in his compendium *Gesammelte Werke* (a collection of Kepler's works made in 1938).

Because of the importance of Kepler as a physicist, and the importance of his records of SN 1604, this supernova is often called Kepler's supernova.

For many years, it was not clear which type of supernova it was. There were discussions on whether it was a core-collapse supernova or a thermonuclear one.

X-ray studies have shown that the O/Fe ratio in the remnant of SN 1604 corresponds to that of an SN Ia (Kinugasa & Tsunemi 1999; Reynolds et al. 2007). In this supernova remnant, there are signs that the system might have been relatively massive, one of its components creating a detached circumstellar shell (CSM) of $1 M_{\odot}$ expanding into the interstellar medium (Vink 2008). Recent studies of this CSM suggest that it had lost contact with the inner evolving stars years before the explosion (Katsuda et al. 2015).

In agreement with this line of thought, some authors have suggested that the companion star could have been an asymptotic giant branch (AGB) star that had lost its envelope (Chiotellis et al. 2012). The dust content of Kepler's supernova remnant also seems to suggest an AGB origin (Williams et al. 2012). As Vink (2016) outlined, the location of the dust emission indicates that all the dust is associated with a shocked CSM, and not with a supernova ejecta. This is a characteristic

of SNe Ia, which do not seem to produce dust in the ejecta (Williams et al. 2012), unlike core-collapse SNRs like Cas A or SN 1987A.

All of the discussions concerning the progenitor of the Kepler supernova are haunted by the lack of precision in the estimated distance. The supernova is located well above the Galactic plane, at $l = 4^{\circ}5$, $b = 6^{\circ}4$ (Vink 2008). It has an angular size of 2 arcmin. The suggested distances to the remnant lie between 3 and 7 kpc. One of the first distances was obtained by Reynoso & Goss (1999), using the H I absorption to the remnant to give a constraint of $4.8 < d_{\text{Kepler}} < 6.2$ kpc. The first distance given by Sankrit et al. (2005), using the proper motion of the optical filaments, had a value of $3.9^{+1.4}_{-0.9}$ kpc. Vink (2008) gave a distance of ~ 6 kpc, from arguments related to the velocity of the forward shock. Based on the non-detection of TeV gamma-rays by HESS, Aharonian et al. (2008) suggested a distance of >6 kpc. Most recently, Sankrit et al. (2016) have revisited the method based on the proper motion of the filaments to derive a distance of $5.1^{+0.8}_{-0.7}$ kpc.

In the present work, we go back to the method, previously used to understand the Tycho supernova in contemporary cosmological terms (Ruiz-Lapuente 2004), and we make use of the historical records of SN 1604 to reconstruct its light curve. We determine the best stretch of the light curve and the distance to the remnant.

Knowing the distance to the supernova is crucial to the searches for a possible surviving companion in this supernova (Kerzendorf et al. 2014; Ruiz-Lapuente 2014). This knowledge allows us to place luminosity limits on the searches and accurately report the kind of potential companions surveyed.

2. Observations

We have compared the historical records gathered by European and Korean astronomers at the time of the explosion in 1604 with the family of SNe Ia as known today. The supernova occurred in a region of the sky that was often observed because the supernova appeared 3° to the northwest of Mars and Jupiter, which were in conjunction, and about 4° to the east of Saturn. So there were plenty of observations that allowed the determination of the time of the appearance of the

supernova on October 10, despite it being unseen before. The early light curve is very complete, with daily reports on the brightness of the supernova. The discovery preceded the visual maximum by 20 days. This means that we have data for three weeks, a lapse that compares well with the best follow-ups currently done on early discovered supernovae. But, unlike Tycho’s SN, which was circumpolar, SN 1604 was observed from Europe and Korea at relative low latitude, and during the months of November and December, the supernova was not observable at night.

The most recent reconstruction of the historical records has been made by Clark & Stephenson (1977, hereafter CS77), who compared the records obtained by Korean astronomers with those obtained by European astronomers, which were previously examined by Baade (1943). Comparison between the Korean and European records gives good agreement in the early part of the light curve, before and around maximum, but there is some disagreement in the phase after the maximum.

High surveillance of the supernova in epochs before its maximum (the visual maximum was on November 1, according to the fit to the light curve) was performed in Europe by a group of anonymous observers. Although the early magnitudes came from untrained observers, the fact that the supernova appeared only about 3° northwest of Mars and Jupiter (which were then in conjunction), and about 4° to the east of Saturn, offered a direct comparison of brightness (a luxury that Tycho Brahe did not have). Only on October 17 did Kepler have a chance to see the supernova.

Tycho Brahe’s observations of the supernova of 1572 showed that the Danish astronomer achieved the maximum accuracy of the human eye and was able to distinguish changes in brightness at a few tenths of a magnitude. Therefore, we assigned 0.25 mag and even 0.2 mag to some of his observations.

Johannes Kepler, the Imperial Mathematician who succeeded Tycho Brahe in the court of Prague, brought physics into the modern era when the laws of motion of the planets that were discovered by him were explained by Isaac Newton. He took interest in the supernova SN 1604, but his contribution cannot be compared with his explanation of the orbit of Mars. Kepler used glasses, as he was shortsighted. He had difficulties in differentiating the brightnesses differing by 0.25 mag or more. CS77 found the following comment by Kepler in *De Stella Nova*: “the star it was seen with almost the same magnitude during the whole month of October.” Kepler started to see the “nova” on October 17, but until November 1st it had an increase in magnitude by more than 0.3 mag. Kepler also wrote on February 6: “I left the observatory, not sure whether I had seen any trace of the star. Therefore, it seems to have become too small to be seen even in this clear morning, if it has survived” (CS77, p. 199). The other records are from untrained astronomers. It would have benefitted the reconstruction of the light curve of SN 1604 if the observations by Fabricius had been preserved, as he was known to be an accurate astronomer. Baade (1943) was only able to recover some mention of these observations in Kepler’s collected works. Thus, in general, we judge that the error in the European observations before and after maximum is 0.5 mag.

The descriptions of the brightness of SN 1604 written by the Korean astronomers are simple and the colors that they gave at premaximum are at odds with those of the European

astronomers. Thus, we assign 0.5 mag uncertainty to the values derived for the brightness, the same error bar used for the premaximum values of the European observers.

From both the early and the total light curve, it can be concluded that Kepler SN Ia was a subluminous SN 1991bg-like event. The European records have a late slope declining more slowly than an SN 1991bg-like SN Ia. However, it also does not look like an overluminous SN 1991T-like SN. The best agreement would be with a “normal” SN Ia (see Figures 1 and 2).

2.1. Early Light Curve up to 60 days Past Maximum

SN Ia are not standard candles but calibrated ones. There is a well known correlation between the brightness at the peak of the light curve and its rate of decline. Phillips (1993) gave the first correlation in terms of a parameter Δm_{15} , which is the number of magnitudes of decline of the B light curve in 15 days after maximum brightness. Hamuy et al. (1996b) used it to calibrate the Calan Tololo SN Ia. This method for obtaining the absolute magnitude of an SN Ia in relation to the Hubble constant also includes a correction for the extinction suffered by the supernova due to dust, mostly in the host galaxy.

The early methods for calibrating SNe Ia separately treated the correction from stretch (this one includes the intrinsic color of a given SN Ia of a particular stretch) and the extinction by dust. Later on, Tripp (1998) advocated for the use of two simultaneous determinations of the parameter of stretch and the parameter of color, the latter taking into account the intrinsic color of the SN Ia and the extrinsic color due to dust.

In our present case, the extinction by dust in the Galaxy is very large and it is very well known. This is why we prefer to use the early version of the stretch that did not require fitting a global color term, but to estimate the extinction. The excess $E(B - V)$ is then estimated separately for SN 1604.

Therefore, the data on SN 1604 are compared using the stretch factor s for the characterization of the rate of decline (Perlmutter et al. 1997, 1999; Goldhaber et al. 2001; Nobili et al. 2003). Stretch is a parameter that linearly scales the time axis so that an SN with a high stretch has a relatively slow decay from maximum, and a SN with a low stretch has a relatively fast decay from maximum. The stretch factor s method, used by the Supernova Cosmology Project, quantifies the decline rate of the supernova from data extending up to 60 days after maximum. In the absence of a measurement of the brightness at maximum, the method allows for location of the event within the family of light curves of SNe Ia. Here, we fit the supernova light curve in the V band.

The best agreement of the light curve of SN 1604 is with a supernova with $s \sim 0.9$ ($s = 0.9 \pm 0.13$). In this sense, as in the case of SN 1572, we show a comparison in Figure 1 with the normal supernova SN 1996X, which has an s of 0.889. Also, for comparison, we show the template light curve of an SN Ia with $s = 0.62$, a subluminous 91bg-type SN, and we show the template of a $s = 1.2$ SN Ia like the overluminous SN 1991T. This figure is centered on the early light curve. Values of the data can be seen in Tables 1, 2, and 3.

Comparing the historical records with a stretch $s = 0.9$ supernova template, we obtain a $\chi^2 = 13.235$ for 13 degrees of freedom, which gives a reduced χ^2/dof of 1.02, which is a good fit. In contrast, the fit to the template of a fast-declining, underluminous SN Ia like SN 1991bg, with a $s = 0.62$, has a χ^2 of 21.65 for 7 degrees of freedom, which is a χ^2/dof of

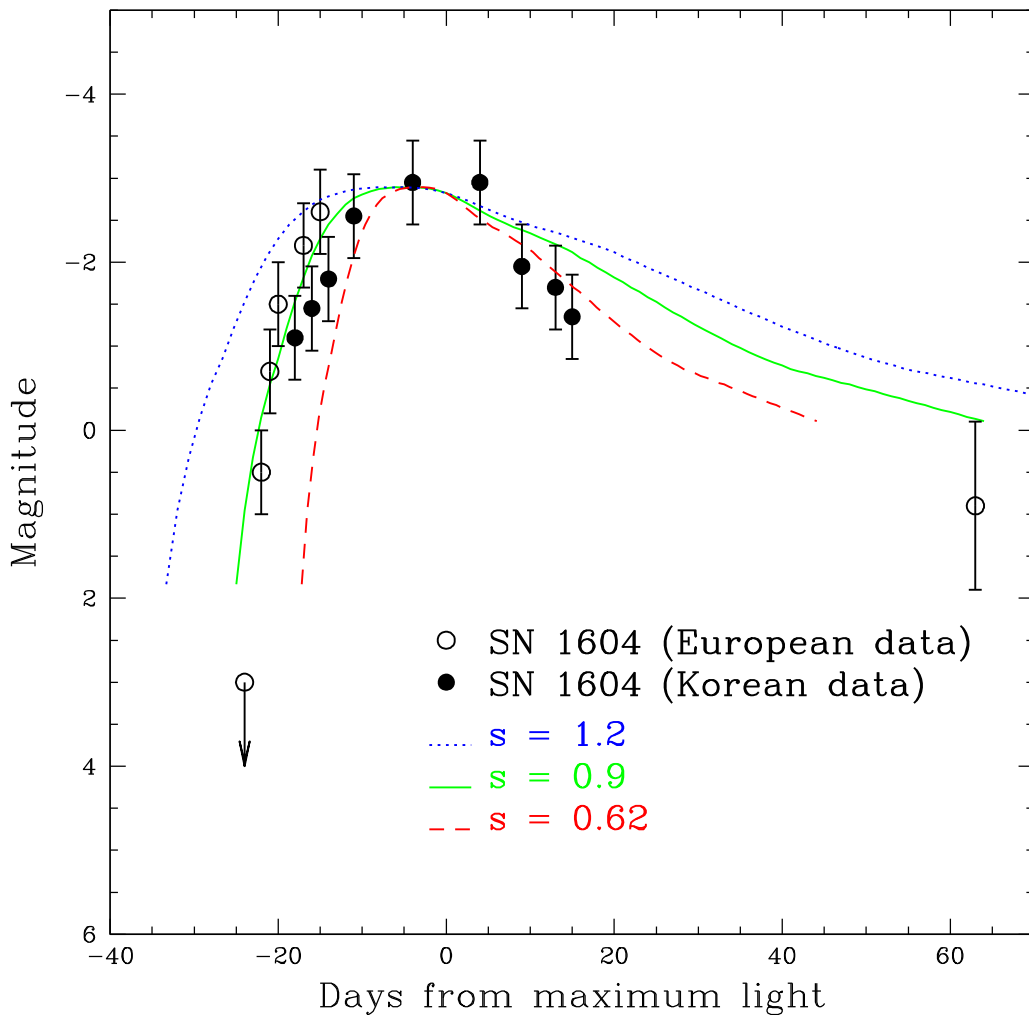


Figure 1. Visual light curve of SN 1604 around maximum light. The Korean records are indicated by filled circles and the European ones are indicated by open circles. The observations are compared with a normal SN Ia with stretch $s = 0.9$, with an overluminous and slow-declining with $s = 1.2$ SN Ia; and with an underluminous and fast-declining with $s = 0.62$ SN Ia.

3.09. In the other extreme, the fit to the template of a slowly declining, overluminous SN Ia like SN 1991T ($s = 1.2$), is the worst one, with a χ^2 of 60.30 for 13 degrees of freedom, which gives a reduced χ^2/dof of 4.64.

We must note that we have performed reasonable estimates of the errors in view of what is reported in the literature. The absolute χ^2 analysis is of limited value because errors are not measured in the light curve, but estimates are used. The fact that the best fit gives $\chi^2/\text{dof} \sim 1$ shows that 0.5 mag is a reasonable estimate of the observational errors. On the other hand, the relative values of the χ^2/dof for different stretch parameters clearly suggest that $s = 0.9$ is much better than stretch factors for overluminous or underluminous SNe Ia.

2.2. Late Light Curve

If one compares the magnitudes of Baade to those of Clark & Stephenson (1977) along the postmaximum decline, one often finds that Baade (1943) subtracts 0.2 mag from what would have been the right magnitude assignment. So, the European magnitudes in CS77 are a bit different from those of Baade (1943), and brighter. Examples of this are the records of April and August. When the recorded comparison says that the star is

as bright as η Oph, which has a visual magnitude of 2.43, Baade assigns 2.6 to the record. CS77 assign 2.40 on one occasion (April 21), but elsewhere they judge the magnitude to be 2.25 (April 12). When the last written records say that the star is as bright as ξ Oph, which is 4.39 mag in V, Baade (1943) rounds the number to 4.5, and Clark & Stephenson (1977) give 4.45. The last two records are similar in Baade (1943) and in CS77, with only a 0.1 mag difference in the assigned brightness of the supernova. Baade (1943) assigns to the record “fainter than ξ Oph,” 5 and 4.8 in visual magnitude, whereas CS77 assign 4.95 and 4.7. Therefore, the disagreement is not significant. According to CS77, Baade ignored the effect of moonlight and the effect of differential extinction when assigning magnitudes to Kepler supernova. CS77 verified the position of the Moon and the phase of the Moon at the time of the supernova observations and found that generally the Moon was not at a critical position that could significantly alter any of the records. CS77 found that differential atmospheric absorption between the supernova and the object of comparison proved significant on a number of occasions. They describe how they took this effect into account. The more accurate treatment of the magnitude assignments leads us to use the records by CS77 instead of those by Baade (1943) when they

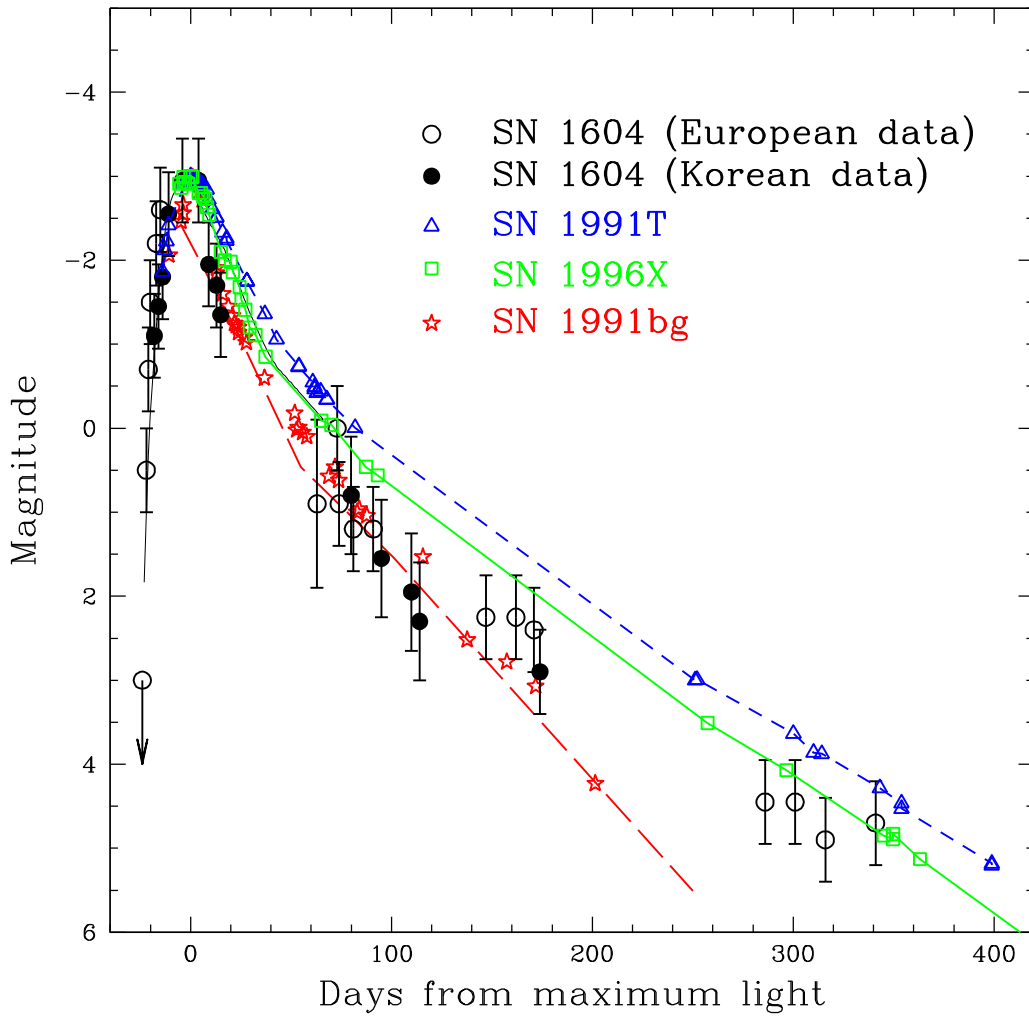


Figure 2. Visual light curve of SN 1604 from the records collected by Baade (1943) and Clark & Stephenson (1977). The supernova is compared with the normal supernova SN 1996X, as well as with the overluminous SN 1991T and the subluminous SN 1991bg.

Table 1
Reduction of the Korean Estimates for SN 1604 to Magnitudes^{a,b}

Date	Phase Adopted	V mag Adopted	Error	Observer Reference	
1604	Oct 14	-17	-1.1	0.5	Korean astronomers
	Oct 16	-15	-1.45	0.5	...
	Oct 18	-13	-1.8	0.5	...
	Oct 19	-12	-2.55	0.5	...
	Oct 28	-3	-2.95	0.5	...
	Nov 5	+4	-2.95	0.5	...
	Nov 10	+9	-1.95	0.5	...
	Nov 14	+13	-1.7	0.5	...
	Nov 16	+15	-1.35	0.5	...
1605	Jan 20	+80	+0.8 (mean)	0.7	...
	Feb 4	+95	+1.55 (mean)	0.7	...
	Feb 19	+110	+1.95 (mean)	0.7	...
	Feb 23	+114	+2.3 (mean)	0.7	...
	April 24	+174	+2.9	0.5	...

Notes.

^a Korean magnitudes are taken from Table 11.3 in CS77.

^b Errors are estimated to be of 0.5 mag, except when they correspond to a mean of observations made on different days. Then the error estimate is judged, as in CS77, to be larger (see Figure 11, 1 of CS77). We assign an error estimate of 0.7 mag for those data.

differ. Overall, the effects are small in comparison with the total error estimate of 0.5 mag to the records.

CS77 located a few postmaximum data in the light curves reported by the Korean astronomers. They plotted huge error bars for those records, which come from the mean of several observations in every case. These are the only points for which CS77 have reported error bars. We assign errors of 0.7 mag to these data.

In Figure 2, we show the supernova light curve compared with those of SN 1996X, SN 1991T, and SN 1991bg. The European records at postmaximum are decisive for classifying SN 1604 as a normal SN Ia, especially the last four. A comparison of the light curve of SN 1991bg with that of SN 1604 gives a $\chi^2/21$ dof, which is $\chi^2/\text{dof} = 5.8$. It is not acceptable. If we want to test the similarity to SN 1991T, we get $\chi^2 = 87.83$ for 31 dof, so $\chi^2/\text{dof} = 2.83$. A comparison of the light curves of SN 1996X and SN 1604 gives a $\chi^2/30$ dof, so $\chi^2/\text{dof} = 1.35$, which seems acceptable.

After 100 days, the rate of decline is 1.37 ± 0.12 V magnitudes in 100 days, according to Baade (1943). This also places the light curve decline among those of normal SNe Ia, which have decline rates of 1.35–1.5 mag in 100 days (see the declines for 1990N and SN 1999bu; for references, see Ruiz-Lapuente 2004).

Table 2
Reduction of the European Estimates for SN 1604 to Magnitudes

Date	Phase Adopted	V mag Adopted	Error	Observer Reference	
1604	Oct 8	−23	+3 or fainter	0.5	Several
	Oct 9	−22	+0.9	0.5	Anonymous physician and others
	Oct 10	−21	+0.5	0.5	Anonymous physician and others
	Oct 11	−20	−0.7	0.5	Anonymous physician and others
	Oct 12	−19	−1.5	0.5	Roeslin
	Oct 15	−16	−2.2	0.5	Physician, Fabricius, Maestlin ^a
	Oct 17	−14	−2.6	0.5	Kepler ^b
1605	Jan 3	+63	+0.9 (mean)	1.0	various and Kepler ^b
	Jan 13	+73	0.00	0.5	Kepler ^b
	Jan 14	+74	+0.9	0.5	Fabricius ^a
	Jan 21	+81	+1.2	0.5	Maestlin ^a
	Jan 31	+91	+1.2	0.5	
	Mar 28	+147	2.25	0.5	
	Apr 12	+162	+2.25	0.5	Fabricius ^a
	Apr 21	+171	+2.40	0.5	Kepler ^a
	Aug 12–14	284–86	+4.45	0.5	Kepler ^b
	Aug 29	+301	+4.45	0.5	Kepler ^b
	Sep 13	+316	+4.95	0.5	Kepler ^b
	Oct 8	+341	+4.7	0.5	Kepler ^b

Notes.^a Kepler (1859).^b Kepler (1938).

Table 3
Colors of Kepler’s Supernova

Date	Phase Adopted	Description	$B - V$ Adopted	Observer Reference	
1604	Oct 8	−23	Not seen	Several	
	Oct 9	−22	Like Mars	1.36	Several
	Oct 15	−16	Like Jupiter	0.82	Unknown physician
	Oct 16				Fabricius and others ^a

Note.^a Kepler (1859).

2.3. Kepler was Neither a SN Ia-CSM Nor Any Other Type of Peculiar SN Ia

SNe Ia that interact heavily with the circumstellar medium have been named SNe Ia-CSM. They are characterized by a narrow $H\alpha$ line on top of an overluminous spectrum. They have much more luminous and flat declines than 91T-like SNe Ia (Silverman et al. 2013).

SNe Ia-CSM (only 0.1%–1% of all SNe Ia) were discovered by Hamuy et al. (2003) in SN 2002ic; they suggested that this supernova could have arisen from a binary system containing a C+O white dwarf plus a massive (3–7 M_{\odot}) AGB star, where the total mass loss in H can reach a few solar masses. Another well-discussed SN Ia-CSM is PTF11kx, observed by Dilday et al. (2012), who suggested that it came from a symbiotic nova progenitor. Soker et al. (2013) noted, however, that the mass around PTF11kx is too high to have been produced by a recurrent nova, and suggested a violent prompt merger of a white dwarf with the core of a massive AGB star.

Katsuda et al. (2015) find that Kepler SN, unlike SN Ia-CSM, should have a dense/knotty CSM located far away

from the progenitor star. They note that the CSM knots were already ~ 2 pc away from the progenitor star at the time of the SN explosion. They also add that the interactions between the CSM and the blast wave started ≥ 200 years after the explosion. And the third piece of evidence is the difference between the historical light curve of Kepler and the light curves of SN Ia-CSM.

In fact, in the paper by Katsuda et al. (2015) it is illustrated how, from the point of view of the light curve of Kepler SN, this one cannot be a SN Ia-CSM. These authors and Vink (2016) qualitatively compare the Kepler SN light curve and other SNe Ia. However, they do not discuss the records and do not aim at template fitting and distance estimates through the light curve, as is done in the present work. Vink (2016) normalizes all the light curves to 5 kpc and stresses that superluminous and subluminous SNe Ia do not match SN 1604’s light curve, at least in a qualitative way.

In Katsuda et al. (2015) it is argued that the amount of Fe found in the X-ray spectrum of the supernova should have synthesized around 1 M_{\odot} of ^{56}Ni . We wonder whether the Fe found could not come from some source different from ^{56}Ni decay, since the light curve does not seem to follow the path of an overluminous SN Ia. One should bear in mind that absolute iron masses are difficult to measure from the X-ray data, as one has to make volume estimates, which are affected by clumping. Thus, Kepler’s iron may come from ^{56}Ni , but perhaps the total mass was less and hence the Si/Fe was different.

Patnaude et al. (2012) showed that some models of SNe Ia have an energy output of $1.4 \cdot 10^{51}$ erg, and having their ejecta interact with a constant density ambient medium can explain the X-ray emission without making the Kepler supernova overluminous. Moreover, Katsuda et al. (2015) assume that the amount of unshocked cold ejecta is the same as in Tycho SNR, in Kepler SNR, and in SNR 0509-67.5. This affects the estimate of unshocked Fe mass. Badenes (2010) found several

differences between Kepler SNR and Tycho SNR that involved aspects of the SN explosion and the ISM and CSM. The modeling of Kepler presents complexities in the morphology and interaction of the CSM that make it difficult to derive parameters like those provided by the parameterized analysis by Katsuda et al. (2015). In general, Badenes (2010) argues in favor of computing a full hydrodynamic evolution of the SNR ab initio, starting from a grid of SN explosion models and ISM and CSM configurations, to calculate the nonequilibrium ionization (NEI) processes in the shocked plasma, and to produce a set of synthetic X-ray spectra that can be compared to observations. This is considered more powerful than individual fits to lines, as it tests the whole physical scenario. To understand the X-ray spectrum of each particular SNR, one has to understand the object as a whole, according to Badenes (2010). There are challenging issues. Some of them are technical, such as the uneven quality of atomic data in X-ray emission codes for NEI plasmas. Then there are other problems that are more fundamental, such as the large uncertainties in the physics of collisionless shocks, particularly the amount of ion-electron temperature equilibration at the shock transition and the impact of cosmic ray acceleration on the dynamics of the plasma.

As we have said, the light curve of the Kepler supernova is very powerful at excluding peculiar types of thermonuclear explosions. The Kepler supernova is clearly not one of the classes of peculiar SNe Ia: SNe Iax, which fall below the Phillips relation being significantly fainter than the bulk of SNe Ia; neither are those fast-declining SNe Ia that, unlike SNe Iax, are not faint at maximum (see examples and references in Ruiz-Lapuente 2014). On the other extreme, it is not a Super-Chandrasekhar supernova with an overluminous magnitude and slow rate of decline. Definitively, SN 1604 lies in the bulk of cosmological SNe Ia.

3. The Distance to Kepler Supernova

We now aim to estimate the distance to Kepler. We think that we have the elements to provide a fairly good estimate.

First of all, we have the new measurements of extinction in the Galaxy provided by Schlafly & Finkbeiner (2011), based on comparisons of the predicted color of stars with observed colors in various surveys. These authors find that the previous estimates by Schlegel et al. (1998) overestimated extinction values in the Milky Way by 14%. The previous values used the infrared emission in the cosmic microwave background (CMB) radiation foregrounds to extract a map of extinction in the Galaxy. The updated value of extinction in the direction of the Kepler supernova by Schlafly & Finkbeiner (2011) is $A_V = 2.7$.

Blair et al. (1991) estimated from the knots in SN 1604 where H_β could not be measured accurately but where H_α was detected, an excess of $E(B - V) = 0.9$. This estimate agrees well with the fact that the supernova at the early premaximum should have had an intrinsic $B - V = -0.05$, though it had an excess $E(B - V) = 0.9$ from the historical records. Those two estimates indicate an extinction $A_V = 3.1 \times E(B - V) = 2.7 \pm 0.1$. We thus assume $A_V = 2.7 \pm 0.1$ for SN 1604.

Concerning the absolute maximum in the visual of the Kepler supernova, it should be $M_V \sim -19.2$ mag. We have already shown that the light curve of the Kepler supernova gives a better fit for a normal SN Ia than for an overluminous or an underluminous SN. We can apply the absolute calibration

for the maximum light of the SN Ia derived by Hamuy et al. (1996a) using the Calan Tololo SN Ia sample. This calibration is $M_{V_{\max}} + 5 \log(H_0/65) = -19.26 \pm 0.12$.

If we take $67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ as the value of H_0 (Ade et al. 2016), then the small error in H_0 carries a $\Delta M_{V_{\max}} = 0.03$. Then we take into account the error associated with the stretch fit. It is carried out by taking into account the uncertainty in fitting the early maximum and the factor multiplying this rate-of-decline fit. This gives a final $\Delta M_V \sim 0.2$ mag. A $M_V = -19.2$ is actually in agreement with a previous indication obtained by modeling the late phases of normal SN Ia (Ruiz-Lapuente 1996). The brightness of Kepler SN Ia at maximum was -3 mag, as bright as Saturn. Then, replacing the values in $M_V = m_V - 5 \log d_p + 5 - A_V$, we obtain $d = 5 \pm 0.7$ kpc. The error in the distance corresponds to a 0.2 mag error in the estimated peak magnitude in V , plus 0.1 in extinction.

4. Summary and Conclusions

The nature of SN 1604, the most recently observed Galactic SN, has been the subject of debate since its discovery, Johannes Kepler being its most famous observer and the most prominent figure in the ensuing disquisitions. Even when its SN nature was acknowledged, there were still discussions about its classification, either as Type I or a Type II SN. That particular point of debate was settled some 10 years ago by X-ray observations of the remnant. But despite being confirmed as a Type Ia, thermonuclear SN, its classification within the SN Ia family has remained unclear.

We have used the historical records on SN 1604, from European and Korean astronomers, to reconstruct the light curve of this SN Ia. This estimate has been based on a combination of the attribution of magnitudes by Baade (1945) and Clark & Stephenson (1977) to the ancient records. We assign a precision according to the information on the records.

The data were then fitted with template light curves, parameterized by the stretch factor s . The best fit corresponds to a “normal” SN Ia, ($s = 0.9 \pm 0.13$). The fit excludes both overluminous events like SN 1991T and subluminous ones like SN 1991bg.

The absolute magnitude of SN 1604 at maximum should have been $M_{V_{\max}} = -19.2$ and the error is calculated according to the error in magnitude coming from the error in stretch and in the calibration linked with H_0 . It is of 0.2 mag in V .

SN 1604 was heavily obscured. Therefore, the amount of extinction suffered plays an important role in the determination of its distance. Based on several coincident measurements, we have $A_V = 2.7 \pm 0.1$ mag.

We obtain a distance to SN 1604 of $d = 5 \pm 0.7$ kpc, in agreement with recent estimates based on the proper motions of the optical filaments of the remnant of the SN, but discarding suggested distances of ~ 6 kpc or more. That is very important for the direct search of a possible surviving companion to the SN.

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References

- Ade, P. A. R., Aghanim, N., Aumont, M., et al. (The Planck Collaboration), 2016, *A&A*, **594**, A13
- Aharonian, F., Akhperjanian, A.G., Barres de Almeida, U., et al. 2008, *A&A*, **488**, 219
- Baade, W. B. 1943, *ApJ*, **97**, 119
- Baade, W. B. 1945, *ApJ*, **102**, 309
- Badenes, C. 2010, *PNAS*, **107**, 7141
- Brahe, T. 1603, in *Astronomiae Instauratae Progymnasmata in Opera Omnia*, Vol. 2, 3 ed. I. L. E. Dreyer (Amsterdam: Swets & Zeitlinger) 1972
- Blair, W. P., Long, K. S., & Vancura, O. 1991, *ApJ*, **366**, 484
- Chiotellis, A., Schure, K. M., & Vink, J. 2012, *A&A*, **537**, A139
- Clark, D. H., & Stephenson, F. R. 1977, *The Historical Supernovae* (Oxford: Pergamon)
- Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, *Sci*, **337**, 942
- Goldhaber, G., Groom, D. E., Kim, A., et al. 2001, *ApJ*, **558**, 359
- Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 1996a, *AJ*, **112**, 2398
- Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 1996b, *AJ*, **112**, 2391
- Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 2003, *Natur*, **424**, 651
- Katsuda, S., Mori, K., Maeda, K., et al. 2015, *ApJ*, **808**, 49
- Kepler, J. 1938, *Gesammelte Werke* (Munich: Deutsche Forschungsgemeinschaft)
- Kepler, J. 1859, *Opera Omnia* (Frankfurt: Frankfurt am Main)
- Kerzendorf, W., Childress, M., Scharwächter, J., Do, T., & Schmidt, B. P. 2014, *ApJ*, **782**, 27
- Kinugasa, K., & Tsunemi, H. 1999, *PASJ*, **51**, 239
- Nobili, S., Goobar, A., Knop, R., & Nugent, P. 2003, *A&A*, **404**, 901
- Patnaude, D. J., Badenes, C., Park, S., & Laming, J. M. 2012, *ApJ*, **756**, 6
- Perlmutter, S., Gabi, S., Goldhaber, G., et al. 1997, *ApJ*, **483**, 565
- Perlmutter, S., Aldering, G., Goldhaber, G., et al. (The Supernova Cosmology Project) 1999, *ApJ*, **517**, 565 (SCP99)
- Phillips, M. M. 1993, *ApJL*, **403**, L105
- Reynolds, S. P., Borkowski, K. J., Hwang, U., et al. 2007, *ApJL*, **668**, L35
- Reynoso, E. M., & Goss, W. M. 1999, *AJ*, **118**, 926
- Ruiz-Lapuente, P. 1996, *ApJL*, **465**, L83
- Ruiz-Lapuente, P. 2004, *ApJ*, **612**, 357
- Ruiz-Lapuente, P. 2014, *NewAR*, **62**, 15
- Sankrit, R., Blair, W. P., Delaney, T., et al. 2005, *AdSpR*, **35**, 1027
- Sankrit, R., Raymond, J. C., Blair, W. P., et al. 2016, *ApJ*, **817**, 36
- Schlafly, E. P., & Finkbeiner, D. P. 2011, *ApJ*, **737**, 103
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, **500**, 525
- Silverman, J. M., Nugent, P. E., GalYam, A., et al. 2013, *ApJS*, **207**, 3
- Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2013, *MNRAS*, **431**, 1541
- Tripp, R. 1998, *A&A*, **331**, 851
- Vink, J. 2008, *ApJ*, **689**, 231
- Vink, J. 2016, in *Handbook of Supernovae*, ed. A. W. Alsabti & P. Murdin (Berlin: Springer), 1
- Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2012, *ApJ*, **755**, 3W