The Crab Nebula's Secret Past: Analysis of the Historical Light Curve of SN 1054 and Implications for the Progenitor

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ABSTRACT

Having undergone core-collapse ~ 1000 years ago, the progenitor of SN 1054 has been the subject of much debate with the core-collapse mechanism and supernova classification still to be determined. In this paper, I present a comparison of the historical observations of SN 1054 with light curves of 11 other core-collapse supernovae from the *Open Supernova Catalog*. I determine the best-fitting light curve to the historical SN 1054 observations to be that of SN 2004dj. I extract the irradiated power over a time period of 642 days since maximum light for each light curve and determine a linear relationship between the irradiated power $\log P_{642}$ and the progenitor mass $\log M_{prog}$. Using this trend, I estimate the progenitor mass of SN 1054 from the irradiated power of SN 2004dj to be 20 $M_\odot$ while the progenitor mass is well established to be $\sim 8-10\ M_\odot$. this estimate of $\sim$twice the known value indicates that SN 1054 is more luminous than expected for its progenitor mass. From this result, and through comparisons with the other light curves used in this study, I conclude that SN 1054 can most likely be classified as a type II-P, the result of the Fe-core collapse of a low-mass red supergiant. Although, future analyses may indicate that SN 1054 could be a low-energy electron-capture supernova, resulting in a type IIn-P event.

1. INTRODUCTION

The Crab Nebula is one of the most famous supernova (SN) remnants in our sky. The nebula and the Crab Pulsar it encapsulates originated from the core collapse supernova (CCSN) SN 1054. Chinese astrologers in 1054 AD were able to see the explosion in broad daylight with the naked eye (see Lundmark 1921; Duyvendak 1942). Today, the remnant consists of an extended nebula exhibiting bright hydrogen emission and a central pulsar left behind after the death of its progenitor (Smith 2013). It is widely accepted that SN 1054 was a CCSN because of the bright hydrogen emission lines in the nebula's spectrum, which constitutes the criterion for such a classification (Filippenko 1997). The presence of the Crab Pulsar has also established SN 1054 as a CCSN since neutron stars originate in such events (Janka 2012; Smith 2013).

Despite ongoing observations and investigations which have lasted for nearly 1000 years, we have not yet been able to determine the core-collapse mechanism — electron capture process (ECSN, resulting from a $\sim 8-10\ M_\odot$ progenitor with an O-Ne-Mg core. See Wanajo et al. 2011; Janka 2012) or Fe-core process (FeCSN) — or the classification of SN 1054. Many of the observed properties of SN 1054 and the Crab Nebula have left astronomers uncertain about the natures of SN 1054 and its progenitor. For example, SN 1054 has a peak absolute magnitude of ~ -18 mag, which is much greater than the typical peak magnitude of a CCSN (-15.6 mag) and implies a high-energy FeCSN

(Shklovsky 1968; Clark & Stephenson 1977). However, the Crab Nebula has an observed kinetic energy of $\sim 7 \times 10^{42}$ J, which is less than the canonical CCSN kinetic energy of $\sim 10^{43} - 10^{44}$ J, implying a lower energy ECSN (see Smartt 2009; Smith 2013; Martin et al. 2021, and references therein). These conflicting observations have resulted in different theories to explain the discrepancy.

There are two main models used to explain the peculiarities of SN 1054. The more traditional framework, proposed by Chevalier (1977), is an FeCSN model with 90% of its kinetic energy and most of its mass contained in a freely expanding, cold, neutral, outer envelope. However, this envelope has not yet been detected at neither visible, X-ray, nor radio wavelengths (Chevalier 1977; Fesen et al. 1997; Hester 2008; Lundqvist & Tziamtzis 2012). The opposing framework describes SN 1054 as an ECSN (Nomoto et al. 1982; Hillebrandt 1982; Kitaura et al. 2006), which would explain the comparatively low kinetic energy of the explosion (Janka 2012). However, ECSNe also have a lower peak magnitude due to a lower production of Fe-group elements compared to FeCSNe, and a low ^{56}Ni yield is indeed observed in the spectrum of the Crab (Kitaura et al. 2006). Thus, the ECSN model does not explain the nature of the SN in its entirety. Chugai & Utrobin (2000) has added to the ECSN model, proposing that interactions with circumstellar material may have resulted in a higher peak brightness and lower kinetic energy than typically observed since ∼20-30% of the kinetic energy would be converted to radiation (Fesen et al. 1997; Chugai & Utrobin 2000). This model would result in a classification for SN 1054 as a type IIn since it is widely accepted that the narrow hydrogen emission lines that define this classification result from interactions with circumstellar material (Smartt 2009). However, the Crab Pulsar moves at a velocity of $\sim$ 160 km/s, and an ECSN would not yield enough energy to produce a neutron star kick nearly this high (Kaplan et al. 2008; Gessner & Janka 2018).

In this paper, I compare the historical SN 1054 observations to other CCSN light curves and determine the best-fitting light curve to use as a model for SN 1054. I calculate the irradiated power over a period of 642 days since maximum light for each light curve and determine a relationship between irradiated power and progenitor mass. Using this trend and the best-fitting light curve, I calculate the progenitor mass for SN 1054. Finally, I examine this result in the context of recent literature and compare the SN 1054 historical data to the other light curves analyzed in this paper.

2. OBSERVATIONS

Using the methods of Nomoto et al. (2014), observations of SN 1054 were inferred from medieval records:

1. SN 1054 reached peak brightness on July 4, 1054 and had an apparent brightness comparable to Venus in the night sky ($m_V \sim -3.5$ to -5 mag).

2. SN 1054 was visible for 23 days during daylight hours, and on July 27, 1054, reached an apparent magnitude of $m_V \sim -3$ mag.

3. On April 6, 1056, SN 1054 was no longer visible at night, suggesting an apparent magnitude of $m_V \sim 6$ mag.

To account for uncertainties in these measurements, error bars were assumed to be 2 mag and 20 days. Correcting for a distance of 2 kpc and visual extinction of $A_V = 1.6$ mag, these observations were used to construct a V-band absolute magnitude historical light curve of SN 1054 (see Figure 1).

Photometric data were obtained from the *Open Supernova Catalog* (OSC, Guillochon et al. 2017) for 11 CCSNe of types IIb, IIn, II-P, and II-L. The criteria for selecting SN light curves were (1) the availability of V-band photometry for at least 642 days after peak brightness since this is the time period for which SN 1054 observations are reported; and (2) a well-established progenitor mass in literature to facilitate later analyses. These apparent magnitude light curves were converted to absolute magnitude using

$$M_V = m_V - DM - K_{Corr}, \tag{1}$$

where $DM = 5\log(\frac{d_L}{10\ \mathrm{pc}})$ is the distance modulus and $K_{Corr} \approx -2.5\log(1+z)$ is an estimate for K-correction (Hogg et al. 2002). Because this K-correction calculation does not account for photometric filters, the absolute magnitudes presented are approximate. These SN light curves as well as the SN 1054 historical light curve are displayed in Figure 1.

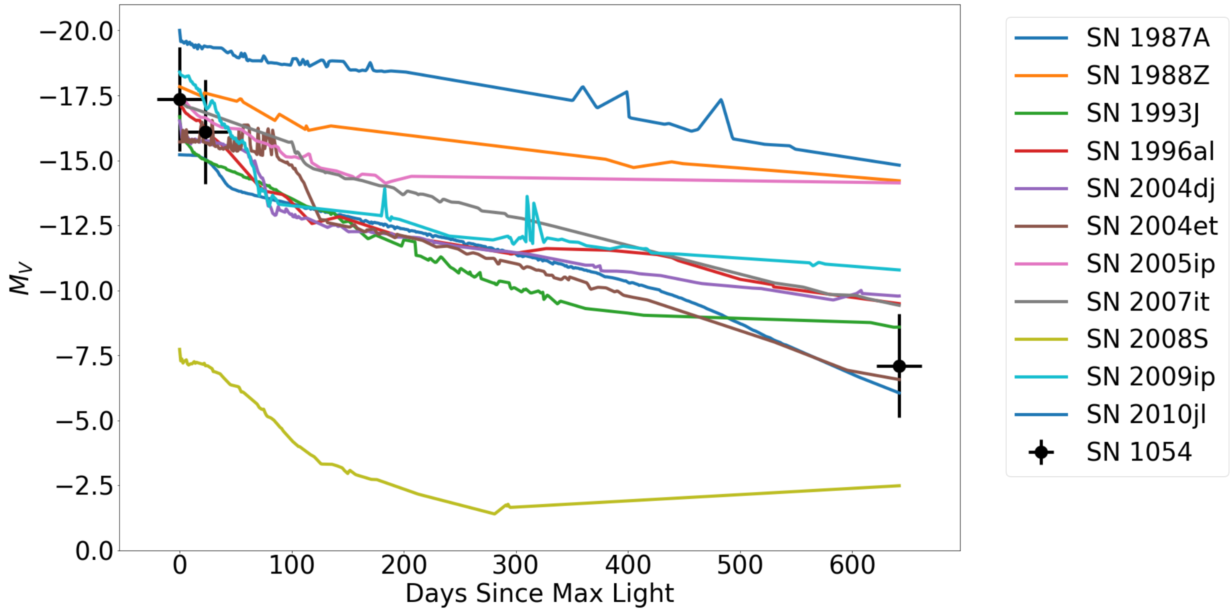

Figure 1. The historical light curve of SN 1054, inferred from medieval records of the object, is displayed in black. The error bars are assumed to be 2 mag and 20 days for each observation. Also shown are 11 CCSN light curves from the OSC, extrapolated from 0 to 642 days after maximum light to match the time period of available SN 1054 observations.

3. METHODOLOGY

The light curves from the OSC were used for comparison with the SN 1054 historical light curve to estimate the progenitor mass. To determine which light curve best fit the SN 1054 historical light curve, χ^2_ν was calculated between each light curve and the observations. The best χ^2_ν value was determined to be 1.0 for SN 2004dj. The light curve for this SN and the SN 1054 data are displayed in Figure 2 for comparison. This light curve was taken to be an approximate model for the SN 1054 historical light curve.

The light curves were converted to luminosity using

$$L = L_0 10^{M_V/-2.5}, \tag{2}$$

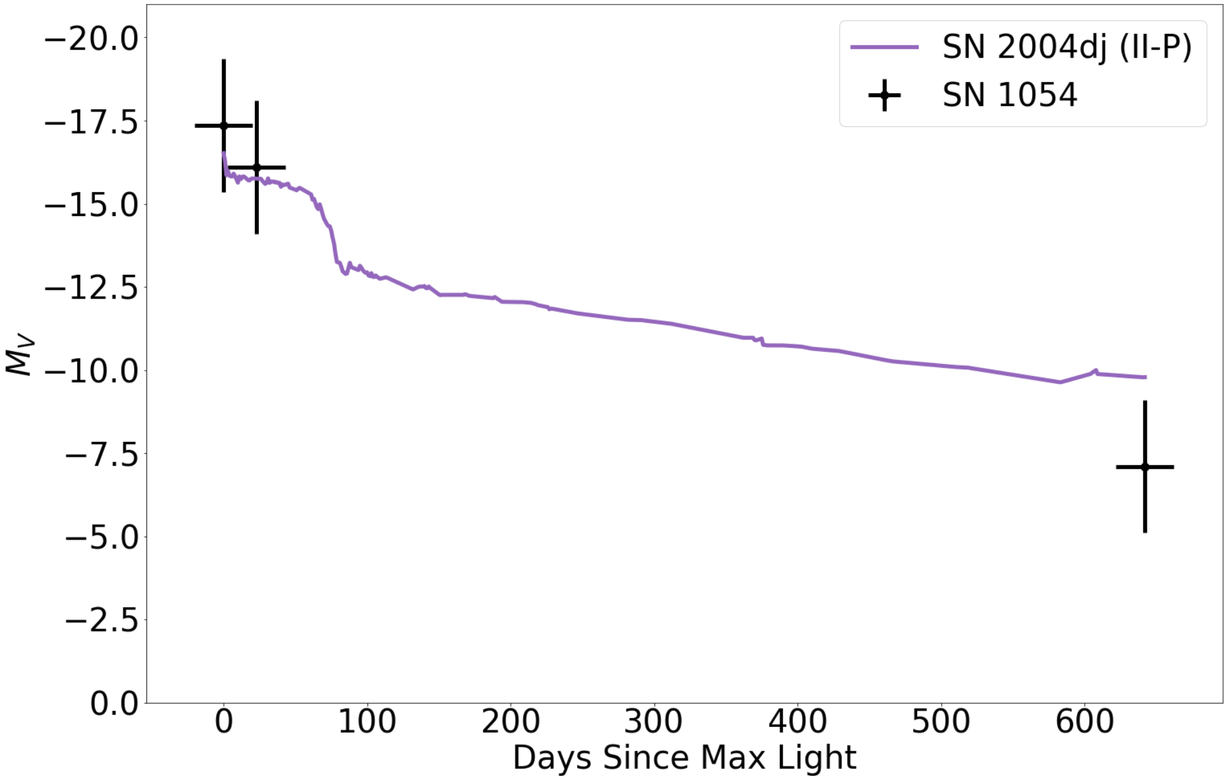

Figure 2. The historical light curve of SN 1054 is plotted in black with error bars of 2 mag and 20 days. The best-fitting light curve, SN 2004dj, is plotted in purple.

where $L_0 = 3.0128 \times 10^{28}\ W$ is the zero-point luminosity. The light curves were then integrated to give the total irradiated power of each SN over the 642-day time period, P_{642}. Progenitor masses for the 11 SNe were obtained from literature and used to calculate a linear trend between $\log P_{642}$ and $\log M_{prog}$. The resulting linear trend is $\log P_{642} = (4.4 \pm 1.5) \log M_{prog} + (30.8 \pm 2.8)$ with P_{642} in W and M_{prog} in $M_\odot$, and the $\log P_{642} - \log M_{prog}$ relationship is shown in Figure 3. The SNe and their corresponding types, χ^2_ν values, progenitor masses, and irradiated powers are listed in Table 1.

Using P_{642} of SN 2004dj and the linear trend, the progenitor mass for SN 2004dj was inferred to be 20 $M_\odot$, which is comparable to the known progenitor mass of SN 2007dj (Table 1, Vinkó et al. 2006). Since SN 2004dj is the best-fitting light curve to the SN 1054 observations, this progenitor mass can be taken as an approximate progenitor mass for SN 1054.

4. DISCUSSION

The SN 1054 progenitor mass is established from literature to be $\sim 8 - 10\ M_\odot$ (Nomoto et al. 1982; Nomoto 1985). Since the progenitor mass reported in this paper, 20 $M_\odot$, is ∼twice the accepted value, SN 1054 most likely has a higher irradiated energy than expected according to the $\log P_{642} - \log M_{prog}$ relationship. This claim is supported by other studies (Shklovsky 1968; Clark & Stephenson 1977), which have concluded a much higher peak brightness of SN 1054 than expected for the kinetic energy of the Crab filaments and the progenitor mass.

The low kinetic energy of the Crab ejecta ($\sim 7 \times 10^{42}\ J$) has led some to conclude that SN 1054 was an ECSN, and the high peak brightness can be explained by a type IIn classification (Chugai & Utrobin 2000; Smith 2013). However, while type IIn SNe are categorized based on their spectra,

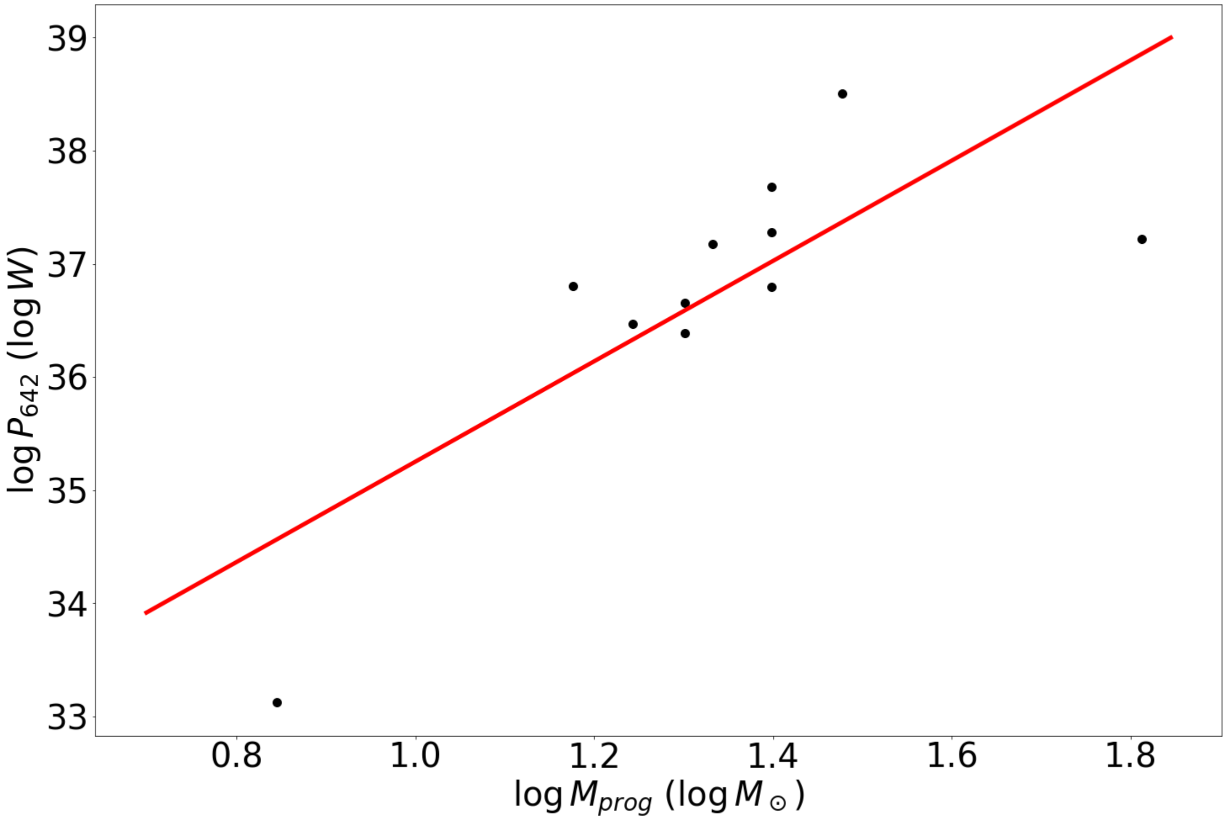

Figure 3. $\log P_{642} - \log M_{prog}$ relationship for the 11 SNe light curves. The data are plotted in black, and the linear trend is shown in red.

Table 1. CCSNe whose light curves were used in analysis. For each SN, the classification, χ^2_ν with SN 1054 observations, progenitor mass and corresponding reference, and irradiated power over the 642-day time period are listed. For progenitor masses reported with uncertainties, the central values were adopted for determining the linear trend in Figure 3.

Supernova	Classification	χ^2_ν	M_{prog} ($M_\odot$)	P_{642} (10^{36} W)
SN 1987A	II-P	0.852	20 (Smith 2007)	2.43
SN 1988Z	II-P	6.62	25 ± 5 (Williams et al. 2002)	48.1
SN 1993J	IIb	0.485	17.5 ± 4.5 (Van Dyk et al. 2002)	2.96
SN 1996al	II-L	0.715	25 (Benetti 2016)	6.24
SN 2004dj	II-P	1.00	20 (Vinkó et al. 2006)	4.50
SN 2004et	II-P	0.396	15 (Jerkstrand et al. 2012)	6.39
SN 2005ip	IIn	6.22	25 Katsuda et al. (2014)	19.1
SN 2007it	II-P	0.740	21.5 ± 5.5 (Andrews et al. 2011)	15.1
SN 2008S	IIn	24.4	7 ± 1 (Botticella et al. 2009)	0.001
SN 2009ip	IIn	1.96	65 ± 15 (Mauerhan et al. 2013)	16.7
SN 2010jl	IIn	9.65	30 (Smith et al. 2011)	319

it is worth noting that all of the type IIn light curves in Table 1 yield the most deviant χ^2_ν values (excluding SN 1988Z) when compared with the historical SN 1054 light curve. In addition, SN 2008S is an ECSN and a type IIn event (Botticella et al. 2009; Stanishev et al. 2008), but its peak brightness is $M_V \sim -7.7$ mag, making it the dimmest SN analyzed in this paper. SN 2008S thus serves as an example of a low-energy ECSN with a type IIn classification, and its low brightness demonstrates why this might not be a suitable framework for SN 1054. Therefore, it is more likely that SN 1054 was an FeCSN with the low observed kinetic energy explained by a freely expanding envelope containing excess kinetic energy not measured in the Crab filaments, as proposed by Chevalier (1977).

From the fit of the SN 2004dj light curve to the SN 1054 observations, SN 1054 could be a type II-P, implying a relatively low-mass red supergiant progenitor (Smartt 2009). The main complication with adopting an FeCSN model, however, is the low ^{56}Ni abundance in the Crab, which is typical for ECSNe. Also, it is worth noting that the SN 2004dj light curve, while yielding a χ^2_ν of 1.0, is outside the error bars of the final SN 1054 observation; at 642 days after maximum light, it becomes evident that the linear portion of the light curve has a steeper slope for SN 1054 than for SN 2004dj. However, the historical data only yields three reliable observations, and these records may not be entirely accurate. So, while a classification of SN 1054 as a type II-P has been proposed in past studies (e.g., Smith 2013), this classification cannot be definitively concluded from the analysis presented here.

However, a type II-P classification for SN 1054 might not be surprising. In a qualitative light curve comparison similar to this study, Smith (2013) suggested that SN 1054 is a type IIn-P, an ECSN that can achieve a relatively high peak brightness that decreases rapidly ∼120 days later due to a low ^{56}Ni abundance, creating the plateau phase in the light curve. This is supported by the low ^{56}Ni abundance in the Crab ejecta, and, assuming type IIn-P are characterized by a high peak brightness comparable to an FeCSN, this could be a suitable classification for the SN 1054 historical light curve. This conclusion is, of course, despite other issues with the ECSN model, such as the high neutron star kick of ~ 160 km/s.

5. CONCLUSIONS AND FUTURE WORK

Upon comparison of the historical SN 1054 light curve with other well-established CCSN light curves, the SN 1054 progenitor should be 20 $M_\odot$ based on calculations of the irradiated power. This result indicates a higher irradiated power of SN 1054 than expected for the known progenitor mass of $\sim 8 - 10\ M_\odot$. In comparison with the light curve of SN 2008S, a type IIn ECSN, SN 1054 is too luminous to be categorized as such. SN 1054 could be a type II-P in comparison with the light curve of SN 2004dj, implying an Fe-core red supergiant progenitor, but limitations imposed by the quantity and quality of the historical data cannot guarantee this result. It is possible that SN 1054 is a type IIn-P in comparison with such light curves (Smith 2013). Analyses of the type IIn-P light curves presented in Smith (2013) — SN 1994W, SN 2009kn, and SN 2011ht — are outside the scope of this paper due to lack of sufficient data in the OSC for at least 642 days after maximum light to facilitate comparisons. However, by acquiring sufficient data in future work, further analyses similar to those presented in this study can be performed. Furthermore, SN light curves only give a partial understanding of these events, so, comparison of the SN 1054 spectrum with other CCSN spectra, following methods similar to those presented here, can yield further limitations and implications for the nature of SN 1054 and its progenitor.

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