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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

Following core-collapse ∼ 1000 years ago, the progenitor of SN 1054 has been the subject of much debate with its 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 estimate a power law relationship between the irradiated power and the progenitor mass. Using this relationship and the irradiated power of SN 2004dj, I estimate the progenitor mass to be $20.7 \pm 9.7\ M_\odot$. This estimate is approximately twice the known value of $\sim 8 - 10\ M_\odot$, which 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, 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, this result is uncertain, and further analyses may confirm that SN 1054 is a low-energy electron-capture supernova due to the low ^{56}Ni yield measured in the Crab Nebula.

1. INTRODUCTION

The Crab Nebula is one of the most famous supernova (SN, plural SNe) 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).

Core-collapse for a $\lesssim 100\ M_\odot$ progenitor can be instigated by either the electron capture process (electron capture supernova, ECSN), resulting from a $\sim 8 - 9\ M_\odot$ progenitor with an O-Ne-Mg core, or the Fe-core process (Fe-core supernova, FeCSN), resulting from a $\sim 9 - 100\ M_\odot$ progenitor (see Wanajo et al. 2011; Janka 2012). In addition, CCSNe are usually H-abundant, resulting in a classification of type II (rather than type I, which are H-deficient; Smartt et al. 2009). Type II SNe can be further classified based on their light curves (type II-P and II-L) and spectra (type IIn and IIb) (Smartt et al. 2009). The light curves of type II SNe exhibit a strong peak in brightness, which decreases on timescales of hundreds of days (LeBlanc 2010). Type II-P SNe exhibit a plateau phase in their light curves after peak brightness where the observed flux is relatively constant, which lasts for ∼ 100 days (Smartt 2009; Kasen & Woosley 2009). The progenitors for this classification are red supergiants with masses of $\sim 8 - 16.5\ M_\odot$ Smartt et al. (2009). Type II-L SNe, on the other hand, exhibit no plateau phase in their light curves. Instead, after reaching a maximum, the brightness decreases linearly with time (Kasen & Woosley 2009; Smartt et al. 2009). Type IIn SNe are classified based on strong narrow hydrogen emission lines in their spectra (Filippenko 1997; Smartt 2009). According to Smartt (2009), these strong emission lines suggest that the ejecta of the explosion interact strongly with circumstellar gas. One possibility for the progenitors of type IIn SNe is luminous blue variables, which eject matter sporadically into the surrounding medium. The high mass-loss rate of these stars could expel the high circumstellar gas density required to produce the observed spectra. Lastly, type IIb SNe begin with strong hydrogen lines in their spectra. The spectra evolve as the hydrogen lines become weaker and disappear while helium lines become stronger, resembling spectra much like those of type Ib SNe (Smartt 2009).

It is widely accepted that SN 1054 was a type II SN (and therefore a CCSN) because of the bright hydrogen emission lines in the nebula's spectrum (Filippenko 1997). The presence of the Crab Pulsar has also established SN 1054 as a CCSN since neutron stars originate from such events (Janka 2012; Smith 2013). However, despite ongoing observations and investigations which have lasted for nearly 1000 years, we have not yet been able to determine the core-collapse mechanism 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 brighter 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 visible, X-ray, or 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). ECSNe also have a lower peak brightness due to a lower production of Fe-group elements compared to FeCSNe (Kitaura et al. 2006). While a low ^{56}Ni yield is indeed observed in the spectrum of the Crab (Kitaura et al. 2006), the peak brightness of SN 1054 is exceedingly high compared to what is expected for an ECSN. Thus, the ECSN model does not explain the nature of this event 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 of 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 (Mauerhan et al. 2013a; Smith 2013). However, the Crab Pulsar moves at a velocity of ~ 160 km/s, and an ECSN would not yield enough energy to produce a neutron star natal 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. In Section 2, I discuss the historical light curve of SN 1054 and the light curves of the CCSNe used in this study. In Section 3, I determine the best-fitting light curve to use as a model for SN 1054. I also 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 relationship and the best-fitting light curve, I calculate the progenitor mass for SN 1054. In Section 4, 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. I present a summary of this study and possibilities for future work in Section 5.

2. OBSERVATIONS

Observations of SN 1054 were inferred by Nomoto et al. (2014) 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.

Following Nomoto et al. (2014), error bars were assumed to be 2 mag and 20 days. The error bars on the magnitudes were doubled from Nomoto et al. (2014) to better account for uncertainties in the measurements. Correcting for a distance of 2 kpc (Trimble 1973) and a visual extinction of $A_V = 1.6$ mag (Miller 1973), these observations were used to construct a V-band absolute magnitude historical light curve of SN 1054 (see Figure 1). The resulting data points are: -17.3 ± 2 mag at 0 ± 20 days since maximum light, -16.1 ± 2 mag at 23 ± 20 days since maximum light, and -7.1 ± 2 mag at 642 ± 20 days since maximum light.

Photometric data for 11 CCSNe were obtained from the *Open Supernova Catalog* (*OSC*), an open-source catalog of data and metadata for SNe and SN candidates (Guillochon et al. 2017). 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 progenitor mass established in literature to facilitate later analyses. By applying these constraints, only one type IIb light curve and one type II-L light curve were used in analysis. However, since SN 1054 is not likely to be either classification (Davidson & Fesen 1985; Smith 2013), the lack of comparisons with numerous type IIb and II-L light curves was not considered to be influential on the analysis. 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). Here, d_L is luminosity distance, and z is redshift. Because this K-correction calculation does not account for photometric filters, the absolute magnitudes presented are approximate (e.g., Guillochon et al. 2017). These SN light curves as well as the SN 1054 historical light curve are displayed in Figure 1.

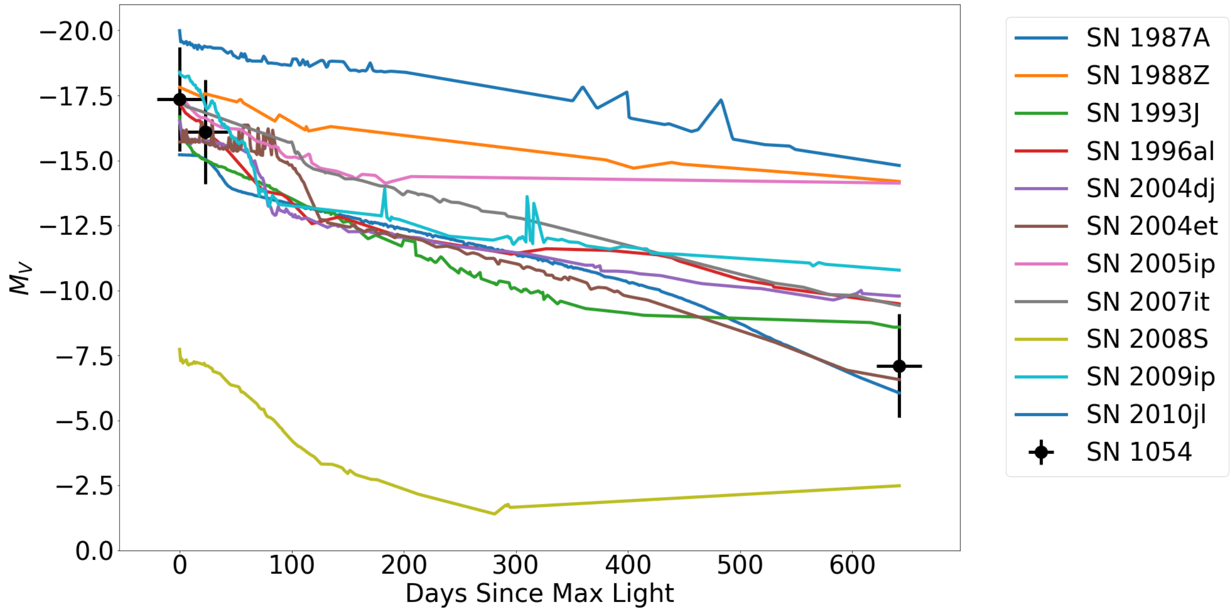

Figure 1. The historical light curve of SN 1054, inferred from medieval records of the object, is displayed in black. The error bars are assumed to be 2 mag and 20 days for each observation. Also shown are 11 CCSN light curves from the *OSC*, extrapolated from 0 to 642 days after maximum light to match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

3. METHODOLOGY

The light curves from the *OSC* were used to estimate the progenitor mass of SN 1054. To determine which light curve best fit the SN 1054 historical light curve, reduced χ^2, or χ^2_ν, was calculated between each light curve and the observations according to:

$$\chi^2_\nu = \frac{1}{\nu}\sum_{i=1}^{n}\frac{(O_i - E_i)^2}{\sigma_i^2}, \tag{2}$$

for ν degrees of freedom (in this case, $\nu = 2$). Here, O_i is the ith data point, E_i is the ith expected value (taken to be the values of each of the 11 SN light curves), σ_i is the uncertainty associated with O_i, and n is the total number of data points (in this case, $n = 3$). The best fitting light curve will result in $\chi^2_\nu \approx 1$. 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 11 light curves were converted to luminosity using

$$L = L_0 10^{M_V/-2.5}, \tag{3}$$

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}, and progenitor masses for the 11 SNe were obtained from literature (see Table 1). The relationship between the explosion energy and the ejecta mass (and therefore the progenitor mass) is established to be a power law, making the log-log relationship between the energy and the progenitor mass linear (see Pejcha & Prieto 2015; Müller et al. 2016, and references therein). Thus, a linear trend was fit to a plot of

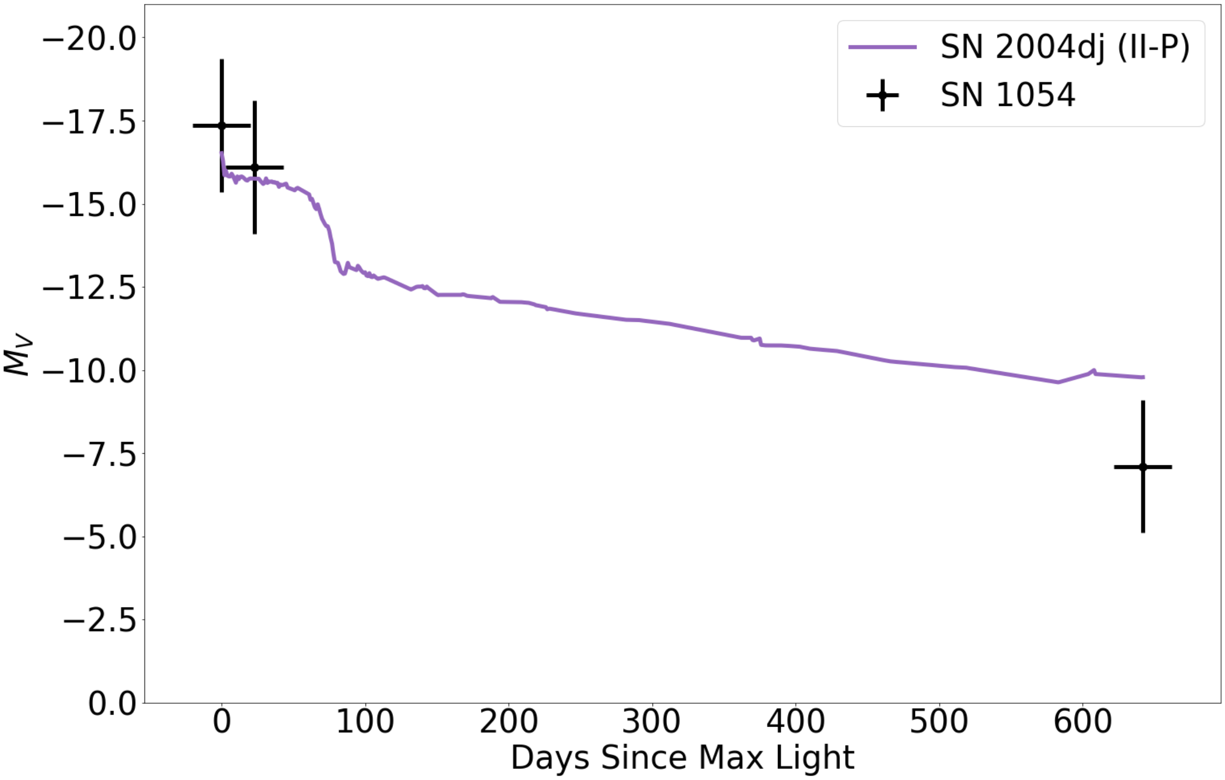

Figure 2. The historical light curve of SN 1054 is shown in black with error bars of 2 mag and 20 days. The best-fitting light curve, SN 2004dj, is shown in purple.

$\log P_{642}$ vs. $\log M_{prog}$, resulting in a linear fit of

$$\log P_{642} = (4.4 \pm 1.5) \log M_{prog} + (30.8 \pm 2.8), \tag{4}$$

with P_{642} in W and M_{prog} in $M_\odot$. For progenitor masses reported with uncertainties (see Table 1), the central values were adopted for determining this trend. 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 (with respective literature), 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 $\sim 20.7\ M_\odot$, which is comparable to the known progenitor mass (Table 1, Vinkó et al. 2006). Since SN 2004dj is the best-fitting light curve to the SN 1054 observations, this estimated value, $20.7 \pm 9.7\ M_\odot$, can be taken as the progenitor mass of SN 1054, with the uncertainty calculated from the error bars assumed for the historical observations. Using this estimated progenitor mass for 2004dj, rather than the value from Vinkó et al. (2006), as the value for SN 1054 avoids the assumption that similar SN light curves are physically identical and that their progenitors have the same mass.

4. DISCUSSION

The SN 1054 progenitor mass is known to be $\sim 8-10\ M_\odot$ from evolutionary models and comparisons to the elemental abundances in the Crab (Nomoto et al. 1982; Nomoto 1985). Since the progenitor mass suggested for SN 1054 in this study, $0.7 \pm 9.7\ M_\odot$, is approximately 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 would explain the discrepancy between the estimated M_{prog} in this paper and

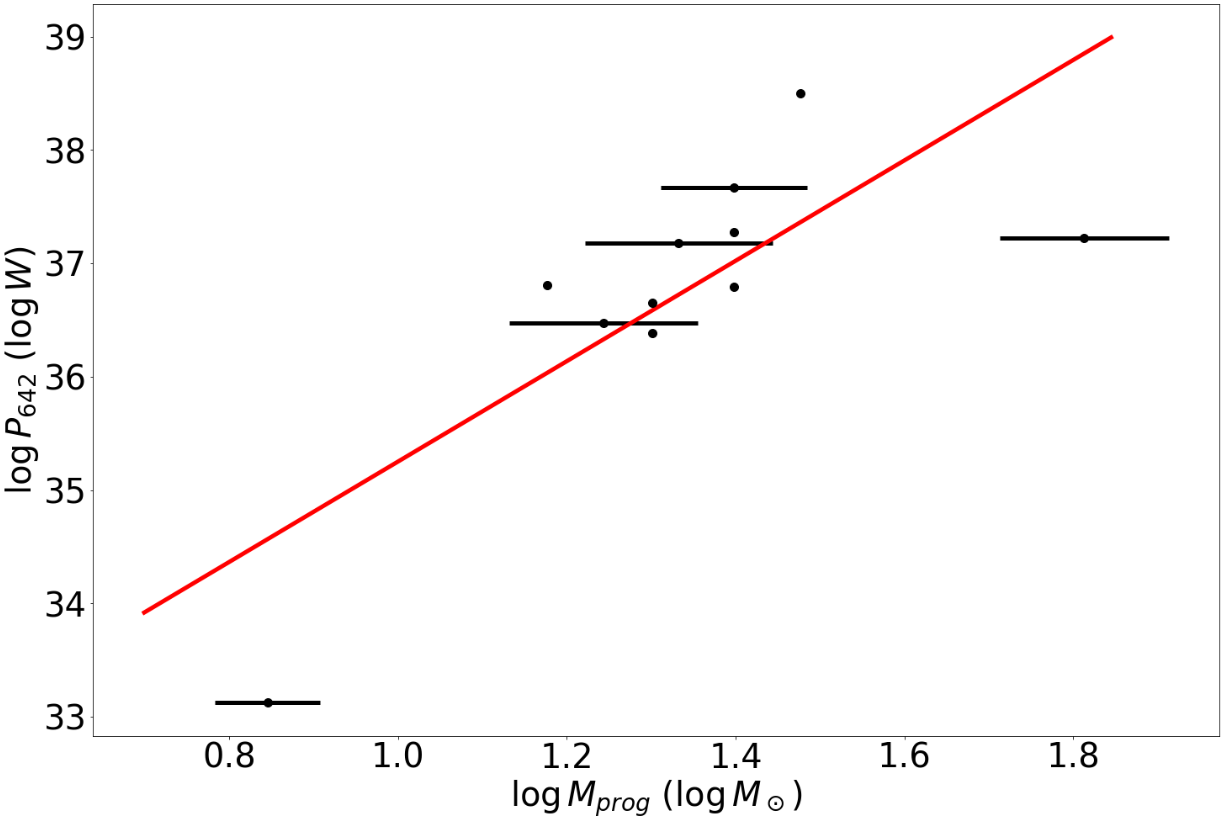

Figure 3. $\log P_{642} - \log M_{prog}$ relationship for the 11 SNe light curves. The data are shown in black, and the linear trend is shown in red. The error bars on correspond to the progenitor mass uncertainties presented in Table 1.

the value reported by other studies. However, the large uncertainty of 9.7 $M_\odot$ indicates a lack of adequate accuracy to make this claim, especially since the lower bound of this result is 11 $M_\odot$, which is comparable to the established $\sim 8-10$ $M_\odot$ range. Nevertheless, other studies (Shklovsky 1968; Clark & Stephenson 1977) claim that SN 1054 had a higher peak brightness than expected for its progenitor mass and the kinetic energy of the Crab filaments.

The low kinetic energy of the Crab ejecta ($\sim 7 \times 10^{42}$ J, see Smith 2013; Martin et al. 2021) has led some to conclude that SN 1054 was an ECSN, and the high peak brightness can be explained by interactions with circumstellar material (Chugai & Utrobin 2000; Smith 2013). This could point to a type IIn classification (Smartt 2009). However, while type IIn SNe are categorized based on their spectra, it is worth noting that all of the type IIn light curves in Table 1 yield the most deviant χ^2_ν values when compared with the historical SN 1054 light curve. This might suggest that SN 1054 might not fit a type IIn classification. In addition, SN 2008S is an ECSN and a type IIn event (Botticella et al. 2009; Stanishev et al. 2008). However, it demonstrates a low peak brightness (see Figure 1) compared to SN 1054 as well as the other SNe analyzed. SN 2008S thus serves as an example of a ECSN with a type IIn classification, but it does not achieve a high irradiated energy like SN 1054. A type IIn ECSN, therefore, might not be a suitable framework for SN 1054 because of the low peak brightness of SN 2008S. 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).

Table 1. CCSNe whose light curves were used in analysis. For each SN, the classification (as listed in the *OSC*), χ^2_ν, progenitor mass and corresponding reference, and irradiated power over the 642-day time period are listed.

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	IIn	6.57	25 ± 5 (Williams et al. 2002)	47.1
SN 1993J	IIb	0.485	17.5 ± 4.5 (Van Dyk et al. 2002)	2.96
SN 1996al	II-L	0.711	25 (Benetti 2016)	6.19
SN 2004dj	II-P	1.00	20 (Vinkó et al. 2006)	4.50
SN 2004et	II-P	0.397	15 (Jerkstrand et al. 2012)	6.38
SN 2005ip	IIn	6.20	25 (Katsuda et al. 2014)	19.0
SN 2007it	II-P	0.737	21.5 ± 5.5 (Andrews et al. 2011)	15.0
SN 2008S	IIn	24.4	7 ± 1 (Botticella et al. 2009)	0.001
SN 2009ip	IIn	1.95	65 ± 15 (Mauerhan et al. 2013b)	16.6
SN 2010jl	IIn	9.61	30 (Smith et al. 2011)	316.

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 (see Smith 2013). 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.

In a qualitative light curve comparison similar to this study, Smith (2013) suggested that SN 1054 is a type IIn-P. 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 SN 1054. This conclusion is, of course, despite other issues with the ECSN model, namely the high neutron star natal kick of ~ 160 km/s measured for the Crab Pulsar (Kaplan et al. 2008; Gessner & Janka 2018).

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 $20.7 \pm 9.7\ M_\odot$ based on calculations of the irradiated power. Since the known progenitor mass of SN 1054 is $\sim 8 - 10\ M_\odot$, this result indicates a higher irradiated power than expected. Because of the high peak brightness of the event and low kinetic energy of the Crab filaments, it has been suggested in past studies that SN 1054 is an ECSN, and interactions with circumstellar material suggest a type IIn classification (Nomoto et al. 1982; Hillebrandt 1982; Chugai & Utrobin 2000; Kitaura et al. 2006). However, 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 also 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 extending the light curves of SN 1994W, SN 2009kn, and SN 2011ht to at least 642 days, possibly through models and simulations, 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. The analysis presented in this paper provides a better understanding of SN 1054 and clearer insight on its nature, contributing to a solution to the ongoing debate about the core-collapse mechanism and classification of the explosion.

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