Modeling The Most Luminous Supernova Associated with a Gamma-Ray Burst, SN 2011kl

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Abstract

We study the most luminous known supernova (SN) associated with a gamma-ray burst (GRB), SN 2011kl. The photospheric velocity of SN 2011kl around peak brightness is 21,000 ± 7000 km s−1. Owing to different assumptions related to the light-curve (LC) evolution (broken or unbroken power-law function) of the optical afterglow of GRB 111209A, different techniques for the LC decomposition, and different methods (with or without a near-infrared contribution), three groups derived three different bolometric LCs for SN 2011kl. Previous studies have shown that the LCs without an early-time excess preferred a magnetar model, a magnetar+56Ni model, or a white dwarf tidal disruption event model rather than the radioactive heating model. On the other hand, the LC shows an early-time excess and dip that cannot be reproduced by the aforementioned models, and hence the blue-supergiant model was proposed to explain it. Here, we reinvestigate the energy sources powering SN 2011kl. We find that the two LCs without the early-time excess of SN 2011kl can be explained by the magnetar+56Ni model, and the LC showing the early excess can be explained by the magnetar+56Ni model taking into account the cooling emission from the shock-heated envelope of the SN progenitor, demonstrating that this SN might primarily be powered by a nascent magnetar.

Key words: stars: magnetars – supernovae: general – supernovae: individual (SN 2011kl)

1. Introduction

The optical spectra of Type Ic supernovae (SNe Ic) lack hydrogen and helium absorption lines (see, e.g., Filippenko 1997; Matheson et al. 2001 for reviews). A small fraction of SNe Ic have spectra with broad absorption troughs indicating large photospheric velocities and were dubbed “broad-lined SNe Ic (SNe Ic-BL)” (Woosley & Bloom 2006). Some SNe Ic-BL have very large kinetic energies (∼1053 erg; e.g., Iwamoto et al. 1998; Mazzali et al. 2000, 2002, 2005; Valenti et al. 2008) and were coined “hypernovae” (Iwamoto et al. 1998). Hypernovae are usually rather luminous (with peak luminosities ∼1043 erg s−1), indicating that they must have synthesized ∼0.5 M⊙ of 56Ni if they can be explained by the radioactive heating model (Arnett 1982; Cappellaro et al. 1997; Valenti et al. 2008; Chatzopoulos et al. 2012). Moreover, some SNe Ic-BL are associated with long-duration gamma-ray bursts (GRBs; e.g., Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003) and have been called “GRB-SNe” (see Hjorth & Bloom 2012; Woosley & Bloom 2006; Cano et al. 2017, and references therein). While most GRB-SNe are Type Ic-BL, not all SNe Ic-BL are associated with GRBs. The most luminous SNe Ic are Type Ic superluminous supernovae (SLSNe; Quimby et al. 2011; Gal-Yam 2012); their peak luminosities are ∼7 × 1043 erg s−1 (Gal-Yam 2012), tens of times greater than those of ordinary SNe.

In this paper, we study a very luminous SN Ic, SN 2011kl, which is associated with an ultralong (T90 ≈ 104 s) GRB 111209A (see, e.g., Golenetskii et al. 2011; Palmer et al. 2011; Gendre et al. 2013; Stratta et al. 2013; Gompertz & Fruchter 2017) at redshift z = 0.677 (Vreeswijk et al. 2011). By using WMAP ΛCDM cosmology (Spergel et al. 2003) and adopting H0 = 71 km s−1 Mpc−1, ΩM = 0.27, and ΩΛ = 0.73, Kann et al. (2016) derived a luminosity distance (DL) of 4076.5 Mpc for GRB 111209A/SN 2011kl. With a peak luminosity ∼3.63 ± 0.16 × 1043 erg s−1 (Kann et al. 2016),8 SN 2011kl is the most luminous GRB-SN yet detected and is significantly more luminous than all other GRB-SNe, whose average peak luminosity is 1 × 1043 erg s−1 with a standard deviation of 0.4 × 1043 erg s−1 (Cano et al. 2017). The time of peak brightness of SN 2011kl is ∼14 days, slightly larger than the average (13.0 days with a standard deviation of 2.7 days; Cano et al. 2017) of other GRB-SNe.

The peak luminosity of SN 2011kl is comparable to that of some not-quite-superluminous “SLSNe” (e.g., PTF11rks, PTF10hgi, iPTF15esz, iPTF16bad, and PS15br) and commensurate with the SN-SLSN gap transients observed by Arcavi et al. (2016); moreover, Liu et al. (2017c) pointed out that the spectrum of SN 2011kl is very different from those of GRB-SNe, but consistent with that of SLSN. So, the energy sources powering its LC might be similar to those powering the SLSN LCs instead of the ordinary SNe Ic. The most popular prevailing models for explaining SLSNe are the magnetar model (Maeda et al. 2007; Kasen & Bildsten 2010; Woosley 2010; Chatzopoulos et al. 2012, 2013; Insaerra et al. 2013; Chen et al. 2015; Wang et al. 2015a, 2016b; Dai et al. 2016; Greiner et al. 2015) found a slightly lower peak luminosity (∼2.81+1.2−1.0 × 1044 erg s−1) since they ignored the near-infrared contribution.
Moriya et al. 2017) and the ejecta plus circumstellar medium (CSM) interaction model (Chevalier 1982; Chevalier & Fransson 1994; Chugai & Danziger 1994; Chatzopoulos et al. 2012, 2013; Liu et al. 2017a). There have been several papers modeling the LCs of SN 2011kl. The LC obtained by Greiner et al. (2015; hereafter the G15 LC) cannot be explained by the $^{56}$Ni model but can be by the magnetar model (Greiner et al. 2015; Cano et al. 2016), the magnetar+$^{56}$Ni model (Metzger et al. 2015; Bersten et al. 2016), the white dwarf tidal disruption event (WD TDE) model (Ioka et al. 2016), and the collapsar model (Gao et al. 2016), involving a stellar-mass black hole and a fallback accretion disk (Woosley 1993; MacFadyen & Woosley 1999). By subtracting the contribution from the ultraviolet (UV)/optical/near-infrared (NIR) afterglow (Kann et al. 2017) of GRB 111209A, Kann et al. (2016) obtained a new bolometric LC (hereafter the K16 LC) and modeled it with the radioactive heating model, finding $2.27 \pm 0.64 M_\odot$ of $^{56}$Ni and $6.79^{+3.67}_{-2.84} M_\odot$ of ejecta, suggesting that this model is disfavored. The LC derived by Ioka et al. (2016; hereafter the I16 LC) has an early-time excess and a dip$^{11}$ that cannot be reproduced by the models mentioned above, but it can be fit by the blue-supergiant (BSG) model with explosive energy injection (“the BSG model”; Kashiyama et al. 2013; Nakauchi et al. 2013; Ioka et al. 2016). However, it is premature to exclude the magnetar model in explaining the I16 LC since the cooling emission from the shock-heated extended envelope (Piro 2015) or the emission from magnetar shock breakout (Kasen et al. 2016) can reproduce the early-time excess.

Thus, the issue of the energy source of SN 2011kl deserves additional attention. In this paper, we reinvestigate the possible mechanisms powering the LC of SN 2011kl and discuss their implications. In Section 2, we use the radioactive heating model, the magnetar model, the magnetar+$^{56}$Ni model, and the magnetar+$^{56}$Ni+cooling model to fit the LCs of SN 2011kl. Our discussion and conclusions are presented in Sections 3 and 4, respectively.

2. Modeling the Light Curves of SN 2011kl

Extracting the LC of an SN associated with a GRB is difficult since this process requires a decomposition of the observations to account for the contributions from the optical afterglow, the SN, and the underlying host galaxy (e.g., Zeh et al. 2004); moreover, it depends on the assumptions adopted for modeling the GRB optical afterglow. By assuming that the LC of the optical afterglow of GRB 111209A can be described by a broken power-law function and subtracting the contributions from the optical afterglow and the host galaxy, Greiner et al. (2015) obtained the LC of SN 2011kl (the G15 LC). The G15 LC did not include the NIR contribution and is a pseudobolometric LC. By adding the NIR contribution, Kann et al. (2016) obtained a genuine bolometric LC (the K16 LC).$^{12}$ However, based on the assumption that the optical afterglow of GRB 111209A can also be described by a single (unbroken) power-law function, Ioka et al. (2016) derived another LC (the I16 LC) for SN 2011kl. This LC has an early-time excess and a dip. Hence, SN 2011kl has three different LCs (see Figure 1) that must be modeled.

The LCs of SLSNe PTF11rks and PTF10hgi (Inserra et al. 2013) are also plotted in Figure 1. By comparing the K16 LC of GRB-SN 2011kl, whose peak luminosity $L_{\text{peak,bol}} \sim 3.6 \times 10^{43} \text{ erg s}^{-1}$, to the LCs of SLSNe PTF11rks and PTF10hgi, we find that the peak of the LC of SN 2011kl is as luminous as that of these two SLSNe. Furthermore, we point out that other SLSNe also have similar values of $L_{\text{peak,bol}}$—e.g., iPTF15lbsb ($L_{\text{peak,bol}} \approx 4 \times 10^{43} \text{ erg s}^{-1}$; Yan et al. 2017), iPTF16bad ($L_{\text{peak,bol}} \approx 4 \times 10^{43} \text{ erg s}^{-1}$; Yan et al. 2017), and PS15br ($L_{\text{peak,bol}} \approx 4.15 \times 10^{43} \text{ erg s}^{-1}$; Inserra et al. 2016).$^{13}$

In this section, we use some models to fit these LCs. For the G15 and K16 LCs, we adopt the Markov Chain Monte Carlo (MCMC) method to minimize the values of $\chi^2$/dof and get the best-fit parameters and the range. For the I16 LC, we do not use the MCMC method because its data have no known error bars.

2.1. The Radioactive Heating Model

Based on their derived LC (the G15 LC), Greiner et al. (2015) fit the $^{56}$Ni model and found that the required mass of $^{56}$Ni is $\sim 1 M_\odot$ if the LC was powered by $^{56}$Ni decay. Kann et al. (2016) suggested that their bolometric LC (the K16 LC),

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$^{9}$ Almost all SLSNe (except maybe pair-instability SLSNe—e.g., SN 2007bi Gal-Yam et al. 2009; but see Dessart et al. 2012 and Nicholl et al. 2013) cannot be explained by the radioactive heating model (Quimby et al. 2011; Inserra et al. 2013; Nicholl et al. 2013, 2014). Some SLSNe I exhibiting late-time rebrightening and Hα emission lines (Yan et al. 2015, 2017) might be powered by a hybrid model containing contributions from magnetars and ejecta-CSM interaction (Wang et al. 2016c).

$^{10}$ Cano et al. (2016) showed that GRB 111209A and SN 2011kl can be explained purely by the magnetar model, both for the afterglow and SN-powered phases.

$^{11}$ This early-time excess arose from the assumption that a single power law could describe the evolution of the optical LC during the afterglow phase. A broken power law showed no such excess (e.g., Greiner et al. 2015; Kann et al. 2016), so this excess is model-dependent. Moreover, a single power law was used by Cano et al. (2016), and no such excess was observed, making it inconclusive.

$^{12}$ The K16 LC must be brighter than the pseudobolometric LC (the G15 LC) without the NIR contribution. However, the median values of the luminosities of the first two points of the K16 LC are dimmer than that of the G15 LC. This fact is puzzling, perhaps indicating that the uncertainties are rather large.

$^{13}$ SN 2011kl, along with PTF11rks, PTF10hgi, iPTF15lbsb, iPTF16bad, and PS15br, are dimmer than the strict threshold for SLSNe ($L_{\text{peak}} > 7 \times 10^{43} \text{ erg s}^{-1}$ and the peak absolute magnitudes $M_{\text{peak}} < -21$ mag in any band; Gal-Yam 2012).
which included the NIR contribution, needed 2.27 ± 0.64 $M_\odot$ of $^{56}$Ni to reproduce its luminosity if the LC was powered by radioactive heating.

Here we employ the semianalytic $^{56}$Ni model (Arnett 1982; Cappellaro et al. 1997; Valenti et al. 2008; Chatzopoulos et al. 2012) to repeat the fits for the G15 LC, the K16 LC, and I16 LC. The free parameters of the $^{56}$Ni model are the optical opacity $\kappa$, the ejecta mass $M_{ej}$, the $^{56}$Ni mass $M_{Ni}$, the initial scale velocity of the ejecta $v_{ej0}$, and the gamma-ray opacity of $^{56}$Ni-cascade-decay photons $\kappa_{\gamma,Ni}$. The value of $\kappa$ is rather uncertain and has been assumed to be 0.06 cm$^2$ g$^{-1}$ (e.g., Arnett 2011; Lyman et al. 2016), 0.07 cm$^2$ g$^{-1}$ (e.g., Chugai 2000; Taddia et al. 2015; Wang et al. 2015b), 0.07 ± 0.01 cm$^2$ g$^{-1}$ (e.g., Greiner et al. 2015; Kann et al. 2016), 0.08 cm$^2$ g$^{-1}$ (e.g., Arnett 1982; Mazzali et al. 2000), 0.10 cm$^2$ g$^{-1}$ (e.g., Inserro et al. 2013; Wheeler et al. 2015), and 0.20 cm$^2$ g$^{-1}$ (e.g., Kasen & Bildsten 2010; Nicholl et al. 2014; Arcavi et al. 2016). Assuming that the dominant opacity source is Thomson electron scattering and the temperature of the SN ejecta consisting of carbon and oxygen is not very high (≤10,000 K), we adopted 0.07 cm$^2$ g$^{-1}$ to be the value of $\kappa$. The value of $\kappa_{\gamma,Ni}$ is fixed to be 0.27 cm$^2$ g$^{-1}$ (e.g., Cappellaro et al. 1997; Mazzali et al. 2000; Maeda et al. 2003; Wheeler et al. 2015). The photospheric velocity of SN 2011kl inferred from the spectra is ~21,000 ± 7,000 km s$^{-1}$ (Kann et al. 2016). We assume that the moment of explosion ($\tau_{\text{expl}}$) for SN 2011kl is equal to that of GRB 111209A.

The LCs reproduced by the radioactive heating models A1, A2, and A3 are shown in Figure 2, and the best-fit parameters are listed in Table 1. While the best-fit model parameters for the G15 LC are approximately equal to that derived by Greiner et al. (2015), our inferred $^{56}$Ni mass (1.42 $^{+0.04}_{-0.04} M_\odot$) for the K16 LC is smaller than the value derived by Kann et al. (2016) (2.27 ± 0.64 $M_\odot$). Moreover, the value of the ejecta mass (4.57 $^{+0.80}_{-1.03} M_\odot$) is also smaller than that derived by Kann et al. (2016) (6.79 $^{+3.62}_{-2.84} M_\odot$).

Another method for estimating the value of $^{56}$Ni is to use the “Arnett law” (Arnett 1982), which says that the $^{56}$Ni energy input LC intersects the peak of the SN LC. According to the Arnett law and Equation (19) of Nadyozhin (1994), the mass of $^{56}$Ni is

$$M_{Ni} = \left( L_{\text{peak}} / 10^{43} \text{ erg s}^{-1} \right) [6.45 \ e^{-t/8.8 \ \text{ days}} + 1.45 \ e^{-t/111.3 \ \text{ days}}]^{-1} M_\odot,$$

(1)

since the value of $t_{\text{rise}}$ of SN 2011kl is ~14 days and the peak luminosity is 3.63 $^{+0.17}_{-0.10} \times 10^{43}$ erg s$^{-1}$ (for the K16 LC) or 2.8 $^{+1.2}_{-0.5} \times 10^{43}$ erg s$^{-1}$ (for the G15 LC), the $^{56}$Ni mass is 1.40 $^{+0.07}_{-0.06} M_\odot$ (for the K16 LC) or 1.08 $^{+0.06}_{-0.08} M_\odot$ (for the G15 LC).

2.2. The Magnetar Model

Greiner et al. (2015) analyzed the spectrum of SN 2011kl and pointed out that the spectral features imply that the $^{56}$Ni mass must be significantly smaller than 1 $M_\odot$; they excluded the $^{56}$Ni model for explaining the LC of SN 2011kl. Alternatively, Greiner et al. (2015) employed the magnetar model developed by Kasen & Bildsten (2010) to fit the G15 LC and obtained a rather good result. But the K16 LC has not yet been fit with the magnetar model.

Here, we use the semianalytic magnetar model developed by Wang et al. (2015a, 2016b) that considers the leakage, photospheric recession, and acceleration effects to fit the K16 LC, and we repeat the fits for the G15 LC. The free parameters of the magnetar model are $\kappa$, $M_{ej}$, the magnetic strength of the magnetar $B_{p}$, the initial rotation period of the magnetar $P_0$, $v_{ej0}$, and the gamma-ray opacity of magnetar photons $\kappa_{\gamma,\text{mag}}$. The value of $\kappa_{\gamma,\text{mag}}$ depends mainly on the energy of the photons ($E_{\text{photons}}$) emitted from the nascent magnetars, varying between ~0.01 and 0.2 cm$^2$ g$^{-1}$ for $\gamma$-ray photons ($E_\gamma \gtrsim 10^6$ eV) and between ~0.2 and 10$^4$ cm$^2$ g$^{-1}$ for X-ray photons ($10^7$ eV ≤ $E_X \leq 10^8$ eV); see Figure 8 of Kotera et al. (2013).

The LCs reproduced by the magnetar models (B1, B2, and B3) are shown in Figure 2 and the best-fit parameters are listed in Table 1. We find that the K16 LC can be powered by a magnetar having $B_p = 5.99_{-5.55}^{+1.75} \times 10^{14}$ G and $P_0 = 10.83_{-2.94}^{+6.45}$ ms, while the G15 LC can be powered by a magnetar with $B_p = 9.72_{-4.13}^{+3.23} \times 10^{14}$ G and $P_0 = 12.07_{-2.53}^{+1.15}$ ms (the values of $B_p$ and $P_0$ derived by Greiner et al. (2015) are ~6~9 × 10$^{14}$ G and ~13.4 ms, respectively).

2.3. The Magnetar Plus $^{56}$Ni Model

The contribution of $^{56}$Ni cannot be ignored when modeling some luminous SNe Ic (Metzger et al. 2015; Wang et al. 2015b; Bersten et al. 2016). Wang et al. (2015b) instead used a hybrid model containing contributions from $^{56}$Ni and a magnetar to fit three luminous SNe Ic-BL whose peak luminosities are approximately equal to that of SN 2011kl. Metzger et al. (2015) and Bersten et al. (2016) used the same model to fit SN 2011kl, suggesting that 0.2 $M_\odot$ of $^{56}$Ni must be added so that a better fit can be obtained. Therefore, we used the hybrid model (the $^{56}$Ni+magnetar model) to fit the K16 LC and the G15 LC. The free parameters of this model are $\kappa$, $M_{ej}$, $M_{Ni}$, $B_p$, $P_0$, $v_{ej0}$, $\kappa_{\gamma,Ni}$, and $\kappa_{\gamma,\text{mag}}$.

Since an energetic SN explosion can synthesize ~0.2 $M_\odot$ of $^{56}$Ni (Maeda & Tominaga 2009; Nomoto et al. 2013), we assumed that the range of $^{56}$Ni is 0~0.2 $M_\odot$ (for the G15 and K16 LCs with error bars, which allow us to use the MCMC method and determine the best-fit parameters) or 0.2 $M_\odot$ (for the I16 LC without error bars). The LCs reproduced by the $^{56}$Ni+magnetar model (C1, C2, and C3) are shown in Figure 2 and the best-fit parameters are listed in Table 1. We find that this hybrid model can also reproduce good fits, and that almost all parameters (except for $P_0$) adopted by the $^{56}$Ni+magnetar model are the same as that of the magnetar models. Moreover, the masses of $^{56}$Ni determined by the MCMC are 0.11±0.06 $M_\odot$ (for the K16 LC) and 0.10±0.06 $M_\odot$ (for the G16 LC).

2.4. The Magnetar Plus $^{56}$Ni Plus Cooling Model

The I16 LC has an early-time excess, which cannot be reproduced by the $^{56}$Ni model, the magnetar model, or the magnetar+$^{56}$Ni model (A3, B3, and C3, respectively; see

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14 The scale velocity of the ejecta $v_{ej0}$ is the velocity of the surface of the ejecta. The radius of the ejecta can be calculated from $R(t) = R(0) + v_{ej0} - t$ (Arnett 1982).

15 Equation (19) of Nadyozhin (1994) is valid only in the case of full gamma-ray trapping. For partial gamma-ray trapping $\left(\kappa_{\gamma,Ni} = 0.027 \text{ cm}^2 \text{ g}^{-1}\right)$, however, the inferred $^{56}$Ni mass is equal to that corresponding to the case of full gamma-ray trapping, because the gamma-ray leakage does not influence the luminosity before and around the LC peak.
The WD-TDE model proposed by Ioka et al. (2016) also cannot explain the I16 LC (see Figure 1 of Ioka et al. 2016). Ioka et al. (2016) suggested that the I16 LC can be explained by the BSG model. Here, we use another model to explain the I16 LC. We suggest that the early-time excess might be due to the cooling emission from the shock-heated extended envelope (Nakar & Piro 2014; Piro 2015), while the main peak of the LC might be powered by a magnetar or a magnetar plus a moderate amount of $^{56}$Ni. In this scenario, the progenitor of the SN is surrounded by an extended, low-mass envelope, which is heated by the SN shock and produces a declining bolometric LC when it cools. At the same time, sources at the center of the SN release energy and produce a rising LC until it peaks. By combining the magnetar ($+^{56}$Ni) model developed by Wang et al. (2015b, 2016b) and the cooling model developed by Piro (2015), an LC with an early-time excess and a dip can be produced. In this model, two additional parameters must be added: the mass of the extended envelope ($M_{\text{env}}$) and the radius of the extended envelope ($R_{\text{env}}$).

The LCs reproduced by the cooling model and the magnetar$+^{56}$Ni+cooling model (D1–D3) are shown in Figure 2 and the corresponding parameters are listed in Table 1. We find that the magnetar$+^{56}$Ni+cooling models (D2 and D3) can well fit the entire I16 LC. In the scenario containing the contribution from the cooling emission, the progenitor of SN 2011kl was supposed to be surrounded by an extended envelope whose mass and radius are $\sim 0.63 M_\odot$ (or $\sim 0.45 M_\odot$) and $\sim 51.4 R_\odot$ (or $\sim 103 R_\odot$), respectively. Owing to the parameter degeneracy, there must be other choices of these two parameters.

One advantage of the magnetar-dominated model is that it can explain the I16 LC if the cooling emission from the extended envelope is added, and it can explain the K16 LC and the G15 LC if the progenitor was not surrounded by an extended envelope. Another advantage is that the LC reproduced by the model with cooling emission can trace the entire LC (including the early excess, the dip, the peak, and the post-peak), while the LC reproduced by the BSG model is a smooth, monotonically decreasing LC that is brighter than the dip and dimmer than the peak. Although the uncertainties of the early-time data indicate that the LC reproduced by the BSG model might fit the data, the magnetar$+^{56}$Ni+cooling model can give a better match.

### 2.5. Summary

In summary, the K16, G15, and I16 LCs cannot be powered solely by the $^{56}$Ni model since (a) $\sim 1.00–1.42 M_\odot$ of $^{56}$Ni is inconsistent with the spectral analysis performed by Greiner...
Table 1
Parameters of Various Models for SN 2011kl

| Model | $\rho_c$ (cm$^{-3}$) | $M_{ej}$ (M$_\odot$) | $M_{env}$ (M$_\odot$) | $R_{env}$ (R$_\odot$) | $M_{Ni}$ (M$_\odot$) | $B_p$ (10$^{15}$ G) | $P_0$ (ms) | $V_{keo}$ (km s$^{-1}$) | $K_{56Ni}$ (cm$^2$ g$^{-1}$) | $\chi^2$/dof |
|-------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|---------------------|---------------------|-----------------|
| A1 (K16ni007) | 0.07 | 4.57±0.80 | ... | ... | ... | 1.42±0.04 | ... | ... | 22.905±23546.1 | 0.027 | ... | 0.353 |
| A1' (K16ni010) | 0.10 | 3.24±0.72 | ... | ... | ... | 1.45±0.05 | ... | ... | 21.710±13413.2 | 0.027 | ... | 0.356 |
| A1" (K16ni020) | 0.20 | 1.71±0.40 | ... | ... | ... | 1.64±0.05 | ... | ... | 19.535±9945.4 | 0.027 | ... | 0.360 |
| A2 (G15ni007) | 0.07 | 3.32±0.79 | ... | ... | ... | 1.06±0.05 | ... | ... | 20.387±9467.2 | 0.027 | ... | 0.061 |
| A2' (G15ni010) | 0.10 | 2.44±0.59 | ... | ... | ... | 1.11±0.05 | ... | ... | 19.866±8566.9 | 0.027 | ... | 0.062 |
| A2" (G15ni020) | 0.20 | 1.50±0.48 | ... | ... | ... | 1.25±0.06 | ... | ... | 19.993±3724.1 | 0.027 | ... | 0.092 |
| A3 (H16ni007) | 0.07 | 2.12 | ... | ... | ... | 1.1 | ... | ... | 21.000 | 0.027 | ... | ... |

For the magnetar models, we have:

| Model | $\rho_c$ (cm$^{-3}$) | $M_{ej}$ (M$_\odot$) | $M_{env}$ (M$_\odot$) | $R_{env}$ (R$_\odot$) | $M_{Ni}$ (M$_\odot$) | $B_p$ (10$^{15}$ G) | $P_0$ (ms) | $V_{keo}$ (km s$^{-1}$) | $K_{56Ni}$ (cm$^2$ g$^{-1}$) | $\chi^2$/dof |
|-------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|---------------------|---------------------|-----------------|
| B1 (K16mag007) | 0.07 | 3.83±0.76 | ... | ... | ... | 0 | 5.99±1.75 | 10.83±0.49 | 21.715±3929.1 | 0.027 | ... | 0.259 |
| B1' (K16mag010) | 0.10 | 3.20±1.23 | ... | ... | ... | 0 | 6.62±1.37 | 10.94±0.35 | 21.159±6405.1 | 0.027 | ... | 0.398 |
| B1" (K16mag020) | 0.20 | 1.94±1.16 | ... | ... | ... | 0 | 6.75±1.38 | 11.08±0.30 | 20.672±4698.9 | 0.027 | ... | 0.361 |
| B2 (G15mag007) | 0.07 | 4.76±1.78 | ... | ... | ... | 0 | 9.72±3.23 | 12.07±1.15 | 20.846±3874.7 | 0.027 | ... | 0.065 |
| B2' (G15mag010) | 0.10 | 3.81±2.23 | ... | ... | ... | 0 | 9.40±3.90 | 10.01±3.49 | 21.517±6103.3 | 0.027 | ... | 0.066 |
| B2" (G15mag020) | 0.20 | 3.10±2.22 | ... | ... | ... | 0 | 12.20±3.97 | 9.26±3.35 | 20.798±6027.5 | 0.027 | ... | 0.066 |
| B3 (I16mag007) | 0.07 | 2.12 | ... | ... | ... | 0 | 6.5 | 13.2 | 21.000 | ... | 10$^4$ | ... |

For the magnetar+$^{56}$Ni models, we have:

| Model | $\rho_c$ (cm$^{-3}$) | $M_{ej}$ (M$_\odot$) | $M_{env}$ (M$_\odot$) | $R_{env}$ (R$_\odot$) | $M_{Ni}$ (M$_\odot$) | $B_p$ (10$^{15}$ G) | $P_0$ (ms) | $V_{keo}$ (km s$^{-1}$) | $K_{56Ni}$ (cm$^2$ g$^{-1}$) | $\chi^2$/dof |
|-------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|---------------------|---------------------|-----------------|
| C1 (K16magni007) | 0.07 | 4.50±1.76 | ... | ... | ... | 0.11±0.06 | 6.94±1.51 | 11.46±0.46 | 21.763±4440.4 | 0.027 | ... | 0.409 |
| C1' (K16magni010) | 0.10 | 3.11±1.19 | ... | ... | ... | 0.11±0.06 | 6.80±1.85 | 11.3±1.01 | 20.334±3638.9 | 0.027 | ... | 0.413 |
| C1" (K16magni020) | 0.20 | 1.69±0.72 | ... | ... | ... | 0.11±0.05 | 7.12±1.43 | 11.4±1.03 | 21.537±4858.5 | 0.027 | ... | 0.406 |
| C2 (G15magni007) | 0.07 | 4.37±1.32 | ... | ... | ... | 0.10±0.05 | 10.07±3.93 | 12.21±3.65 | 19.410±5356.7 | 0.027 | ... | 0.403 |
| C2' (G15magni010) | 0.10 | 3.66±1.70 | ... | ... | ... | 0.11±0.05 | 10.48±9.10 | 10.80±3.95 | 20.051±3415.6 | 0.027 | ... | 0.071 |
| C2" (G15magni020) | 0.20 | 2.93±1.36 | ... | ... | ... | 0.10±0.05 | 14.10±4.33 | 10.47±3.62 | 20.857±3581.1 | 0.027 | ... | 0.069 |
| C3 (I16magni007) | 0.07 | 2.12 | ... | ... | ... | 0.2 | 6.5 | 14.2 | 21.000 | 0.027 | ... | 0.13 |

For the magnetar+$^{56}$Ni+cooling models, we have:

| Model | $\rho_c$ (cm$^{-3}$) | $M_{ej}$ (M$_\odot$) | $M_{env}$ (M$_\odot$) | $R_{env}$ (R$_\odot$) | $M_{Ni}$ (M$_\odot$) | $B_p$ (10$^{15}$ G) | $P_0$ (ms) | $V_{keo}$ (km s$^{-1}$) | $K_{56Ni}$ (cm$^2$ g$^{-1}$) | $\chi^2$/dof |
|-------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|---------------------|---------------------|-----------------|
| D1 (I16cooling) | 0.07 | 2.12 | 0.63 | 51.4 | 0 | ... | ... | ... | 21.000 | 0.027 | ... | ... |
| D2 (I16magnicooling) | 0.07 | 2.12 | 0.63 | 51.4 | 0.2 | 6.5 | 14.2 | 21.000 | 0.027 | 0.13 | ... |
| D2" (I16magnicooling) | 0.07 | 1.6 | 0.45 | 103 | 0.2 | 6.5 | 14.2 | 16.000 | 0.027 | 0.13 | ... |

Note. The uncertainties are 1σ.
+ The cooling+magnetar+$^{56}$Ni model (D2 = D1 + C3).
et al. (2015), and (b) the ratio of $^{56}$Ni masses (\(\sim 1.0-1.4 M_\odot\)) to the ejecta mass (\(\sim 2-5 M_\odot\)) is \(\sim 0.3\), which is significantly larger than the upper limit (\(\sim 0.20\); Umeda & Nomoto 2008). Alternatively, the K16 and G15 LCs can be explained by the magnetar model and the $^{56}$Ni+ magnetar model; the values of $M_{\text{ej}}$, $B_p$, and $P_0$ can be found in Table 1.

Owing to the degeneracy of model parameters, the values of these parameters have many choices that can also give the best-fit LC. For example, Bersten et al. (2016) obtained $P_0 = 3.5$ ms, $B_p = 1.95 \times 10^{15}$ G, $M_{\text{ej}} = 2.5 M_\odot$ if \(\kappa = 0.2\) cm$^2$ g$^{-1}$, and $M_\text{Ni} = 0.2 M_\odot$; Metzger et al. (2015) derived $P_0 \approx 2$ ms, $B_p \approx 4 \times 10^{14}$ G, $M_{\text{ej}} = 3 M_\odot$ if \(\kappa = 0.2\) cm$^2$ g$^{-1}$, and $M_\text{Ni} = 0.2 M_\odot$; and Cano et al. (2016) derived $P_0 = 11.5-13.0$ ms, $B_p = (1.1-1.3) \times 10^{15}$ G, and $M_{\text{ej}} = 5.2 M_\odot$ if \(\kappa = 0.07\) cm$^2$ g$^{-1}$.

3. Discussion

3.1. What Determines the Peak Luminosities of SNe and SLSNe?

The inferred best-fit values of $P_0$ and $B_p$ of the magnetar powering the LCs of SN 2011kl are \(\sim 9-14\) ms and \((6-14) \times 10^{14}\) G, respectively. The values of $P_0$ obtained by Bersten et al. (2016), Metzger et al. (2015), and Cano et al. (2016) are 3.5 ms, 2 ms, and 11.5-13.0 ms (respectively), while the respective values of $B_p$ derived by these groups are $1.95 \times 10^{15}$ G, \(\sim 4 \times 10^{14}\) G, and (1.1-1.3) \(\times 10^{15}\) G. The spin-down timescale of a magnetar ($\tau_p$) is determined by the values of $P_0$ and $B_p$, \(\tau_p = 1.3(B_p/10^{14}\text{G})^2(P_0/10\text{ms})^2\) years (Kasen & Bildsten 2010). We note that other SLSNe Ic whose peak luminosities are larger than \((2.0-2.5) \times 10^{51}\) erg (the ejecta mass is lower than $2.4 M_\odot$ for the K16 LC or $1.4 M_\odot$ for the G15 LC), the origin of $E_{K,0}$ of SN 2011kl ($E_{K,0} = 0.3 M_\odot V_{\text{ej}}^2 \approx 2.4 \times 10^{51}$ erg) can be comfortably explained by the neutrino-driven magnetar model. However, the values of $M_{\text{ej}}$ are proportional to that of \(\kappa^{-1}\), while the values of all other parameters are completely independent of that of $M_{\text{ej}}$.

Assuming $\kappa = 0.10$ and 0.20 cm$^2$ g$^{-1}$, and using the $^{56}$Ni model, the magnetar model, and the magnetar plus $^{56}$Ni model, we repeated the fits for the K16 LC and the G15 LC, obtaining the best-fit parameters (see Table 1).

By comparing the values of the parameters corresponding to different values for $\kappa$, we found that while the values of the ejecta masses are significantly influenced by the values of $\kappa$ and $M_{\text{ej}} = a \kappa^{-1} + b$ (a and $b$ are constants; see Figure 3, and a similar figure can be found in Nagy & Vinkó 2016), all other parameters are slightly affected by the values of $\kappa$ and no correlation between them and $\kappa$ has been found.

We did not study the correlations between the opacity and other parameters for the I16 LC, since its data lack error bars, and the value of $M_{\text{ej}}$ is proportional to that of $\kappa^{-1}$, while the values of all other parameters are completely independent of that of $M_{\text{ej}}$.

3.3. The Initial Kinetic Energy of SN 2011kl

The multidimensional simulations (see Janka et al. 2016, and references therein) for neutrino-driven SNe suggest that the value of $E_K$ provided by the neutrinos can be up to \((2.0-2.5) \times 10^{51}\) erg. Provided the value of $V_{\text{ej,0}}$ is 14,000 km s$^{-1}$ (the ejecta mass is lowered to $2.4 M_\odot$ for the K16 LC or $1.4 M_\odot$ for the I16 LC), the origin of $E_{K,0}$ of SN 2011kl ($E_{K,0} = 0.3 M_\odot V_{\text{ej}}^2 \approx 2.4 \times 10^{51}$ erg) can be comfortably explained by the neutrino-driven model and other processes are not required to provide additional $E_{K,0}$.

According to the equation $E_{K,0} \approx (1/2) \int \rho^2 v^2 dt \approx 2 \times 10^{52}(P_0/1\text{ms})^2$ erg (I \(\approx 10^{45}\) cm$^2$ is the rotational inertia of the magnetar), we find that the initial rotational energy of the magnetar ($P_0 = 11.4-14.2$ ms) powering the LCs of SN 2011kl is \(\sim 1.5 \times 10^{50}\) erg (Cano et al. 2016 obtained $E_{K,0} = (1.2-1.6) \times 10^{50}$ erg), significantly smaller than their $E_{K,0}$. Even if the initial rotational energy of this magnetar is all converted to the $E_{K,0}$ of the ejecta, the ratio of final $E_K$ to $E_{K,0}$ is \(\sim 1.1\). Therefore, the acceleration effect is rather small and can be neglected.

3.4. The Ejecta Mass and Binarity

Assuming that $\kappa = 0.07$ cm$^2$ g$^{-1}$ and according to the results of our work based on the magnetar models (the $^{56}$Ni models have been excluded), the inferred ejecta mass of SN 2011kl is $3.83^{+0.20}_{-0.14} M_\odot$ (for the K16 LC), $4.76^{+0.05}_{-0.07} M_\odot$ (for the G15 LC), or $\sim 2.12 M_\odot$ (for the I16 LC). If $\kappa = 0.10$ cm$^2$ g$^{-1}$ or 0.20 cm$^2$ g$^{-1}$ were adopted, the inferred masses would decrease by a factor of about 2-3, \(\sim 1-2 M_\odot\).

By adopting $\kappa = 0.04$ cm$^2$ g$^{-1}$ and $V_{\text{ej,0}} = 20,000$ km s$^{-1}$, Ioka et al. (2016) concluded that the mass of the ejecta is $2 M_\odot$ if SN 2011kl is powered by a magnetar. Assuming that $\kappa = 0.07$ cm$^2$ g$^{-1}$ and $V_{\text{ej,0}} = 21,000$ km s$^{-1}$, the ejecta mass must be $2 M_\odot \times 0.04/0.07 \times 21,000/20,000 = 1.323 M_\odot$, significantly smaller than the value derived here (2.12 $M_\odot$).

This difference is caused by the fact that we adopted the equation $\tau_m = (2 \kappa M_{\text{ej}}/3 \beta \nu_{\text{ej}} c)^{1/2}$, while Ioka et al. (2016) adopted the equation $\tau_m = (3 \kappa M_{\text{ej}}/4 \beta \nu_{\text{ej}} c)^{1/2}$. The ratio of the masses derived from these two equations is $3/4 \beta = 3 \times 13.8/8 \times 3.1416 = 1.647$. By multiplying this factor by $1.323 M_\odot$, we obtain $2.18 M_\odot$, consistent with the value derived here (2.12 $M_\odot$). The ejecta mass would be $1.45 M_\odot$ if $\kappa = 0.1$ cm$^2$ g$^{-1}$ and $\tau_m = (2 \kappa M_{\text{ej}}/3 \beta \nu_{\text{ej}} c)^{1/2}$.
Ioka et al. (2016) and Arcavi et al. (2016) argued that the ejecta mass of SN 2011kl inferred from the magnetar model is too low to be produced by a core-collapse SN whose remnant harbors a magnetar. However, it must be pointed out that such a small value is not disfavored by the explosion of an SN Ic and magnetar formation, since the massive hydrogen and helium envelopes of the progenitors of SNe Ic had been stripped by their companions or winds, and the mean value of the ejecta mass of SNe Ic is 2.9 $M_\odot$ with a standard deviation of 2.2 $M_\odot$ (see Table 6 of Lyman et al. 2016). The inferred ejecta masses of Type Ic-BL SNe 2002ap, 2006aj, 2009bb, and 2010bh are $2.0^{+0.8}_{-0.7} M_\odot$, $1.4^{+0.4}_{-0.2} M_\odot$, $1.9^{+0.6}_{-0.5} M_\odot$, and $0.9^{+0.2}_{-0.2} M_\odot$, respectively (see Table 5 of Lyman et al. 2016). Note, especially, that SN 2006aj with $M_{ej} = 1.4^{+0.4}_{-0.2} M_\odot$ (or $\sim 2 M_\odot$; Mazzali

Figure 3. Correlation between the ejecta mass and the opacity for SN 2011kl.
et al. 2006) is an SN Ic-BL associated with an X-ray flash (a “soft GRB”) that has long been believed to be powered by a nascent magnetar (Mazzali et al. 2006). Such small ejecta masses indicate that the progenitor of SN 2011kl might be located in a binary system and most of its mass had been stripped by its companion before the explosion. Although the mass-transfer process reduced the mass of the progenitor, it can enhance the angular momentum and angular velocity of the progenitor, making it easier for the nascent neutron stars left by the SN explosions to be millisecond ($P_0 \approx 1$–10 ms) magnetars.

4. Conclusions

In this paper, we modeled the LCs of SN 2011kl, which is the most luminous ($L_{\text{peak}} = 3.63^{+0.17}_{-0.16} \times 10^{43}$ erg s$^{-1}$) GRB-SN identified thus far. By using the bolometric LC of SN 2011kl derived by Kann et al. (2016) and assuming that this SN is powered by $^{56}$Ni cascade decay, we find that the required $^{56}$Ni mass is $1.42^{+0.08}_{-0.04} M_{\odot}$, which is smaller than that ($2.27 \pm 0.64 M_{\odot}$) inferred by Kann et al. (2016). The $^{56}$Ni model can be excluded from explaining the LCs of SN 2011kl, since the spectral features indicate that the amount of $^{56}$Ni must be significantly smaller than $\sim 1 M_{\odot}$ (Greiner et al. 2015).

Alternatively, we used the magnetar model and the magnetar+$^{56}$Ni model to fit the K16 LC and the G15 LC, finding that both of the models can well explain these LCs. It is noteworthy that Ioka et al. (2016) argue that the fact that the location of GRB 111209A-SN 2011kl is near the nucleus of the host galaxy favors the WD-TDE model. However, the position of the SN does not necessarily mean that this event must be a TDE rather than an SN. The magnetar model is still possible, explaining the K16 LC and the G15 LC, while the TDE model is also a plausible one for the G15 LC and the K16 LC.

Whereas the magnetar model and the magnetar+$^{56}$Ni model can account for the K16 LC and the G15 LC, they cannot explain the I16 LC because these models cannot produce the early-time excess and the dip, although the presence of the early-time excess is entirely model-dependent (i.e., the parameters of the optical-afterglow component in the LC decomposition technique). To solve this problem, we added the contribution of the cooling emission from a low-mass ($M_{\text{env}} \approx 0.5 M_{\odot}$), extended ($R_{\text{env}} \approx 50$–100 $R_{\odot}$) SN progenitor envelope, and found that the magnetar+cooling model and the magnetar+$^{56}$Ni+cooling model can account for the I16 LC. In these models, cooling emission from the shock-heated envelope powers the early-time excess, while the magnetar or magnetar+$^{56}$Ni power the main peak of the LC, and the sum of these two produces the dip. Hence, we conclude that the BSG model is not unique for explaining the I16 LC even if the LC of SN 2011kl has an early-time excess, since a progenitor surrounded by a low-mass, extended envelope can also power an LC with an early excess.

It seems that the magnetar+$^{56}$Ni+cooling and the magnetar+$^{56}$Ni models are more reasonable than the magnetar and magnetar+cooling models for the LCs of SN 2011kl, since core-collapse SNe must synthesize a moderate amount of $^{56}$Ni. However, discriminating between the LCs reproduced by the models with and without $^{56}$Ni is very difficult because the contribution of a moderate amount of $^{56}$Ni ($\sim 0.1$–0.2 $M_{\odot}$) is significantly smaller than that of the magnetar.

Provided that the initial velocity of the ejecta of SN 2011kl is $\sim 14,000$ km s$^{-1}$ (the lower limit of the ejecta velocity; see Kann et al. 2016), the inferred values of the initial kinetic energy of this SN is $E_{K,0} \approx 2.0 \times 10^{51}$ erg, indicating that the neutrino-driven mechanism (Janka et al. 2016) is able to provide the $E_{K,0}$ for this SN. But larger velocities require other mechanisms to provide additional $E_{K,0}$.

Furthermore, we used an MCMC method for the G15 and the K16 LCs to constrain the range of the model parameters (we did not perform MCMC for the I16 LC owing to the absence of the error bars); see Table 1. By adopting different values of $\kappa$, we found that, while the inferred mass is significantly influenced by the values of $\kappa$ ($M_\nu = a\kappa^{-1} + b$ (a and b are constants)), all other parameters are only slightly affected by the values of $\kappa$ and no correlation between them and $\kappa$ has been found.

According to these results, we suggest that the magnetar and the magnetar+$^{56}$Ni models, with or without the cooling effect, can reproduce the LCs of SN 2011kl. In other words, SN 2011kl might be primarily powered by a nascent magnetar.

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17 It should be mentioned that the model in which the progenitors have a nonstandard structure (Nakar & Piro 2014; Piro 2015) has been employed to explain some SLSNe whose bolometric LCs exhibit an early-time excess (Smith et al. 2016; Vreeswijk et al. 2017).

18 We caution that the question of how the magnetar powers an ultralong GRB is still unsolved. Metzger et al. (2015) suggested that a magnetar with $P_0 \approx 2$ ms and $B_0 \approx 4 \times 10^{14}$ G can power the ultralong GRB 111209A and SN 2011kl, but Beniamini et al. (2017) demonstrated that it is difficult for a magnetar to produce an ultralong GRB. This issue is beyond the scope of this paper and needs additional research. Moreover, we do not attribute the optical afterglow of GRB 111209A to magnetar spin-down emission.
