A Monte Carlo Approach to Magnetar-powered Transients. I. Hydrogen-deficient Superluminous Supernovae

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Abstract

In this paper we collect 19 hydrogen-deficient superluminous supernovae (SLSNe) and fit their light curves, temperature evolution, and velocity evolution based on the magnetar-powered model. To obtain the best-fitting parameters, we incorporate the Markov chain Monte Carlo approach. We get rather good fits for seven events ($\chi^2$/dof = 0.24–0.96) and good fits for another seven events ($\chi^2$/dof = 1.37–3.13). We find that the initial periods ($P_0$) and magnetic strength ($B_p$) of the magnetars that supposedly power these SLSNe are in the range of $\sim$1.2–8.3 ms and $\sim$(0.2–8.8) $\times 10^{14}$ G, respectively; the inferred masses of the ejecta of these SLSNe are between 1 and 27.6 $M_\odot$, and the values of the gamma-ray opacity $\kappa_{\gamma}$ are between 0.01 and 0.82 cm$^2$ g$^{-1}$. We also calculate the fraction of the initial rotational energy of the magnetars harbored in the centers of the remnants of these SLSNe that is converted to the kinetic energy of the ejecta and find that the fraction is $\sim$19%–97% for different values of $P_0$ and $B_p$, indicating that the acceleration effect cannot be neglected. Moreover, we find that the initial kinetic energies of most of these SLSNe are so small ($\lesssim 2 \times 10^{51}$ erg) that they can be easily explained by the neutrino-driven mechanism. These results can help clarify some important issues related to the energy-source mechanisms and explosion mechanisms and reveal the nature of SLSNe.

Key words: stars: magnetars – supernovae: general

1. Introduction

Superluminous supernovae (SLSNe; Quimby et al. 2011a; Gal-Yam 2012), whose peak luminosities are $\gtrsim 10^{44}$ erg s$^{-1}$, have been discovered and studied in the past decade. According to their optical spectra near maximum light, SLSNe can be divided into Types I (hydrogen-deficient) and II (hydrogen-rich); the detailed classification schemes of SNe based on their spectra were summarized by Filippenko 1997; Gal-Yam 2016). To date, all SLSNe I are Type Ic SNe whose spectral features resemble those of the normal-luminosity SNe Ic (Pastorello et al. 2010; Gal-Yam 2012; Inserra et al. 2013; Nicholl et al. 2016a). While most SLSNe II have narrow H$\alpha$ emission lines in their optical spectra and can be regarded as the high-luminosity versions of normal SNe II, a few SLSNe II do not have H$\alpha$ emission lines but have spectra resembling those of SNe III (Gezari et al. 2009; Miller et al. 2009; Inserra et al. 2016).

The problems of the origin of the energy sources and explosion mechanisms of SLSNe have not yet been completely solved. Currently, the most prevailing energy-source models explaining SLSNe are the magnetar-powered model (e.g., Kasen & Bildsten 2010; Woosley 2010; Dessart et al. 2012; Inserra et al. 2013; Chen et al. 2015; Wang et al. 2015a, 2016c, 2016d; Dai et al. 2016), the ejecta–circumstellar medium (CSM) interaction model (Chevalier 1982; Chevalier & Fransson 1994; Chugai & Danziger 1994; Chugai 2009; Chevalier & Irwin 2011; Chatzopoulos et al. 2012; Ginzburg & Balberg 2012), and the pair instability supernova (PISN) model (Barkat et al. 1967; Rakavy & Shaviv 1967), which is essentially $^{56}$Ni-powered (Colgate & McKee 1969; Colgate et al. 1980; Arnett 1982) but requires a huge amount ($\gtrsim 5 M_\odot$) of $^{56}$Ni. Some SLSNe show double-peaked light curves (Nicholl et al. 2015a; Nicholl & Smartt 2016; Smith et al. 2016; Vreeswijk et al. 2017), and their early-time excess emission might be due to the cooling emission from shock-heated envelopes of the progenitors, while the main peaks can be explained by the magnetar-powered model or interaction model. Determining the energy-source models for SLSNe is rather tricky. For example, Gal-Yam et al. (2009) proposed that SN 2007bi, whose light-curve decline rate is approximately equal to the decay rate of $^{56}$Co, is a PISN, but Dessart et al. (2012) argued that it might not be a PISN since its spectrum is inconsistent with the spectrum produced by the PISN model; Nicholl et al. (2013) demonstrated that another slow-declining SLSN, PTF12dam, whose post-peak light curve mimics that reproduced by the PISN model, is not yet a PISN since the rising part of its light curve cannot be explained by the PISN model.

Except for the two high-redshift SLSNe (SN 2213–1745 and SN 1000+0216) that are believed to be PISNe (Cooke et al. 2012) and SN 2007bi, whose explosion mechanism is still under debate, all SLSNe discovered cannot be explained by the PISN model since the ratio of required masses of $^{56}$Ni to inferred ejecta masses is too large and/or the theoretical light curves did not fit the observational data (Quimby et al. 2011a; Inserra et al. 2013;}

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5 It has long been recognized that the dipole radiation from the nascent neutron stars can enhance the luminosities of the normal SNe (Ostriker & Gunn 1971; Maeda et al. 2007).
This fact, in turn, indicates that most SLSNe observed might be core-collapse SNe (CCSNe) since the peak luminosities of SNe Ia cannot reach $10^{44} \text{ erg s}^{-1}$.\footnote{SNe Ia magnified by the gravitational lensing effect, e.g., PS1-10afx (Quimby et al. 2011b, 2014), are not genuine SLSNe.}

SLSNe that cannot be explained by the PISN model can be explained by the magnetar-powered model (Inserra et al. 2013; Nicholl et al. 2013, 2014) or the ejecta–CSM interaction model (e.g., Smith & McCray 2007; Moriya et al. 2013; Nicholl et al. 2014). The magnetar-powered model proposes that the nascent neutron stars with initial rotational periods of a few milliseconds and magnetic strength of $10^{15}–10^{15} \text{ G}$ inject their rotational energy into the ejecta of SNe, while the ejecta–CSM interaction model supposes that the interaction between the SN ejecta and the CSM surrounding the progenitors of the SNe can release a huge amount of energy and heat the SN ejecta. These two processes can significantly enhance the luminosities of the SNe and lead them to be SLSNe.

In this paper we focus on the SLSNe that were demonstrated not to be PISNe. While the ejecta–CSM model cannot be excluded in explaining these SLSNe Ic, we do not adopt it owing to the absence of the interaction signatures (e.g., narrow He emission lines) that are indicative of strong interaction between the ejecta and CSM. Studies have shown that the magnetar-powered model can well reproduce the light curves of these SLSNe, and indicated that the magnetar-powered model has special advantages since it does not need ad hoc assumptions about the pre-SN mass-loss history. Therefore, the magnetar model is preferred in modeling SLSNe Ic.

Most previous studies using the magnetar-powered model focused on the light-curve fitting. Some group fitted the light curves, temperature evolution, and the evolution of photospheric radii of SLSNe. However, the photospheric radius of an SLSN cannot be measured directly, and it is derived from the luminosity and temperature ($L = 4\pi\sigma\theta^4R^2$, where $L$ is the luminosity, $\sigma$ is the Stefan–Boltzmann constant, $T$ is the temperature, and $R$ is the photospheric radius).

In this paper, we collect a sample of 19 SLSNe I and use the magnetar-powered model proposed by Wang et al. (2016c) to fit their light curves, temperature evolution, and velocity evolution. To obtain the best-fitting parameters, we use the Markov chain Monte Carlo (MCMC) code developed by Wang et al. (2017b), who employed this approach (magnetar-powered model + MCMC) to fit the light curves of SN 1998bw and SN 2002ap.

This paper is organized as follows. In Section 2, we present our sample and describe the magnetar-powered model adopted. In Section 3, we use the magnetar-powered model and the MCMC code to get the best-fitting parameters. We discuss implications of our results in Section 4 and give some conclusions in Section 5. In another paper (Wang et al. 2017a), we systematically studied the whole sample of broad-lined SNe Ic not associated with gamma-ray bursts. We find that the magnetar-powered model can also well account for both the light curves and velocity evolution of these SNe.

## 2. Sampling and Modeling

We collect 19 Type I (Ic) SLSNe in the literature; see Table 1. All of these SLSNe have light curves and temperature data, and most of them have velocity data. These SLSNe are selected because the observational errors were provided by the

### Table 1

| SN Name       | Redshift (z) | Peak Luminosity ($10^{44} \text{ erg s}^{-1}$) | Reference |
|---------------|--------------|---------------------------------------------|-----------|
| DES13S2cccm   | 0.663        | 0.63                                        | Papadopoulos et al. (2015) |
| DES14X3tzx    | 0.608        | 2.20                                        | Smith et al. (2016)     |
| Gaia16apdf    | 0.102        | 3.01                                        | Kangas et al. (2017)    |
| LSQ12dfi      | 0.25         | 1.03                                        | Nicholl et al. (2014)   |
| LSQ14mc       | 0.256        | 1.09                                        | Chen et al. (2017)      |
| PS1-10awh     | 0.908        | 2.41                                        | Chomiuk et al. (2011)   |
| PS1-10bzw     | 0.65         | 1.07                                        | Lunnan et al. (2013)    |
| PS1-11ap      | 0.524        | 0.72                                        | McCrum et al. (2014)    |
| PS1-14bj      | 0.521        | 0.46                                        | Lunnan et al. (2016)    |
| PTF10gpi      | 0.099        | 0.35                                        | Inserra et al. (2013)   |
| PTF11rks      | 0.193        | 0.47                                        | Inserra et al. (2013)   |
| PTF12dam      | 0.108        | 1.17                                        | Nicholl et al. (2013)   |
| SN 2010gx     | 0.231        | 0.91                                        | Inserra et al. (2013)   |
| SN 2011ke     | 0.143        | 0.81                                        | Inserra et al. (2013)   |
| SN 2011kf     | 0.245        | 3.72                                        | Inserra et al. (2013)   |
| SN 2012il     | 0.175        | 0.80                                        | Inserra et al. (2013)   |
| SN 2013dg     | 0.26         | 0.74                                        | Nicholl et al. (2014)   |
| SN 2015bn     | 0.114        | 2.42                                        | Nicholl et al. (2016b)  |
| SSS 120810    | 0.17         | 1.04                                        | Nicholl et al. (2014)   |

In order to quantitatively describe the leakage effect associated with gamma and X-ray photons emitted from the magnetar, Wang et al. (2015a) incorporated the trapping factor $(1 - e^{-\frac{D}{L}})$ into the original magnetar-powered model, $A = 3\kappa M_{\text{ej}}/4\pi \rho^2 \kappa_\gamma$, where $\kappa_\gamma$ is the effective gamma-ray opacity.
is not an observable quantity, a free parameter $T_{\text{start}}$ is included to refer to the theoretical explosion time relative to the zero epoch given in the paper from which the observed data have been taken. In the papers providing the data, sometimes the zero epochs refer to the peak times, and otherwise the zero epochs refer to the inferred explosion times.

While the PISN model (pure $^{56}$Ni-powered model) has been excluded by previous studies for most SLSNe I, a moderate amount of $^{56}$Ni synthesized by these SLSNe cannot be completely neglected. However, the masses of $^{56}$Ni synthesized by CCSNe are usually only 0.04–0.2 $M_\odot$ for normal CCSNe and 0.2–0.5 $M_\odot$ (see, e.g., Figure 8 of Mazzali et al. 2013) for some hypernovae
Figure 2. Model fits for light curves, temperature evolution, and velocity evolution of SN 2012il, PTF2dam, PTF11rks, SN 2013dg, SSS 120810, PTF10hgi, Gaia16apd, and DES13S2cm. Parameters are shown in Table 2.
whose kinetic energies were inferred to be $\gtrsim 10^{52} \text{erg}$. When we study an SLSN whose peak luminosities $\gtrsim 10^{44} \text{erg s}^{-1}$, the contribution of $0.1-0.5 M_\odot$ of $^{56}\text{Ni}$ is significantly lower than the contribution from magnetars or the ejecta-CSM interaction and can therefore be neglected (e.g., Inserra et al. 2013; Chen et al. 2015) since $0.1-0.5 M_\odot$ of $^{56}\text{Ni}$ will power a peak luminosity of $\sim 2 \times 10^{42} - 1 \times 10^{43} \text{erg s}^{-1}$ if the rise time is $\sim 18$ days and a lower peak luminosity for longer rise times.

Hence, we neglect the contribution from $^{56}\text{Ni}$ in our modeling, i.e., the mass of $^{56}\text{Ni}$ is set to be zero. In summary, the free parameters in this model are $M_{\text{ej}}$, $B_p$, $P_0$, $V_{\text{sc}0}$, $N_\gamma$, and $T_{\text{max}}$. To get the best-fitting parameters and estimate the uncertainties of the parameters, we use the code developed by Wang et al. (2017b), who incorporated the MCMC approach into our revised magnetar-powered model.

3. Results

Using the magnetar-powered model and the MCMC approach, we find that the light curves, temperature evolution, and velocity evolution reproduced by the model are in excellent agreement with the observational data of LSQ14mo, PS1-10awh, PS1-10bzj, SN 2010gx, SN 2011kf, and PS1-11ap; see Figure 1. The
light curves and temperature data of SN 2012il, PTF12dam, PTF11rks, SN 2013dg, SSS 120810, PTF10hgi, Gaia16apd, and DES13S2cmn can also be explained by the model, but the velocities reproduced by the model are larger or smaller than the data of these SLSNe; see Figure 2. DES13S2cmn is also in this group since it does not have velocity data. The light curves of SN 2011ke, SN 2015bn, LSQ12df, DES14X3taz, and PS1-14bj can also be well reproduced by the model, but both the temperature evolution and velocity evolution of these SLSNe do not fit the theoretical curves well; see Figure 3. In these figures, the zero epochs all refer to the peak times of the SLSN light curves.

The best-fitting parameters and the values of $\chi^2$/ dof are listed in Table 2, and their error bars can be appreciated by inspecting Figure 4. Some parameters, e.g., $v_{\kappa}$ and $v_{\psi}$ of some SNe (see Figure 4), cannot be tightly constrained, and therefore only their $1\sigma$ upper or lower limits are presented in this table. From Table 2, we find that the magnetars’ initial periods and the magnetic field strengths are 1.2–8.3 ms and (0.2–8.8) $\times 10^{14}$ G, respectively, consistent with theoretical expectations and the results of previous modeling. The gamma-ray opacity $\kappa_\gamma$ directly determining the magnitude of the late-time leakage effect is between 0.01 and 0.8 cm$^2$ g$^{-1}$. Assuming that $\kappa_\gamma = 0.1$ cm$^2$ g$^{-1}$, the masses of these SLSNe are between 1 and 27.6 $M_\odot$. Nicholl et al. (2015b) have fitted the light curves of 24 hydrogen-deficient SLSNe and found that the range of their ejecta masses is 3–30 $M_\odot$ if $\kappa_\gamma = 0.1$ cm$^2$ g$^{-1}$. Both the lower limit and the upper limit of the mass range in our sample are smaller than the values inferred by Nicholl et al. (2015b). If we adopt a larger $\kappa_\gamma$, e.g., 0.2 cm$^2$ g$^{-1}$, the ejecta mass must be halved. Although the acceleration effect must be obvious for less massive ejecta, the light curves have only a slight change, i.e., the degeneracy between the $\kappa_\gamma$ and $M_{ej}$ would not be broken.

The initial scale velocity $v_{\psi0}$ of the ejecta of these SLSNe is between $\sim1100$ km s$^{-1}$ and $1.7 \times 10^3$ km s$^{-1}$. Based on the values of $M_{ej}$ and $v_{\psi0}$, the initial KE $E_{K0}$ of these SLSNe can be calculated. In the beginning of the expansion when the acceleration does not take place and the initial KE can be calculated according to $E_{K0} = 0.3 M_{ej} v_{\psi0}^2$ (see Arnett 1982; footnote 1 of Wheeler et al. 2015) and listed in Table 3. The initial rotational energy of the corresponding magnetars and the accumulative fraction ($\eta$) of the magnetars’ rotational energy converted to the ejecta KE are also listed in Table 3.

Figure 5 shows the distributions of these best-fitting parameters (initial periods $P_0$, magnetic strength $B_p$, ejecta masses $M_{ej}$, initial scale velocities $v_{\psi0}$, and the gamma-ray opacity $\kappa_\gamma$), the derived parameter (initial KE $E_{K0}$), and the conversion fraction ($\eta$).

### 4. Discussion

In our adopted model, the initial velocity of the SN ejecta is also a free parameter, rather than a measurable quantity. The magnetar wind would accelerate the ejecta, sweep up the material into a (thin) shell, and produce a bubble between the center and the shell. We fit the observed photospheric velocities $v_{ph}$ (even though they are always smaller than the scale velocities $v_{\psi0}$) and find that the theoretical velocities of the ejecta of six SLSNe are in excellent agreement with the observations. However, we would point out that the velocity data of the remaining SLSNe in our sample cannot be well reproduced by the model.

In most of the previous studies, the KE $E_K$ was a constant since the scale velocity $v_{\psi0}$ is fixed to be a constant ($v_{\psi0} = v_{\psi0}$), and then the inferred KE is equivalent to the initial KE ($E_K = E_{K0}$). This assumption would cause two problems.

First, if we neglect the acceleration effect from the magnetar wind, the ejecta expansion is homologous ($v_{\psi0}(x) \propto x$, where $x$ is the distance between the arbitrary point in the ejecta and the center), and the KE of the ejecta is $E_K = 0.3 M_{ej} v_{\psi0}^2$. According to this formula, we find that the initial KEs of almost all SLSNe in the literature are $\geq 5 \times 10^{51}$ erg if the acceleration effect is neglected. Most SLSNe might be CCSNe, and their initial KE
should be given by neutrinos coming from proto-neutron stars. The multidimensional simulations of neutrino-driven SNe find that the upper limit of the KE provided by neutrinos is \(\sim 2.0 \times 10^{51}\) erg or \(\sim 2.5 \times 10^{51}\) erg (Ugliano et al. 2012; Ertl et al. 2016; Müller et al. 2016; Sukhbold et al. 2016). Even if we adopt the looser upper limit (\(\sim 2.5 \times 10^{51}\) erg), it is still significantly smaller than the inferred KE (\(\gtrsim 5 \times 10^{51}\) erg) of the SLSNe. It seems evident that some other mechanisms are required to provide the additional initial KE.

To solve this problem, one might assume that the energy injection process must be divided into two steps: (1) the magnetar releases \(\gtrsim 3 \times 10^{51}\) erg of the rotational energy at a very short internal ("explosive injection"), and (2) the magnetar continuously injects its rotational energy to SN ejecta ("continuous injection"). As pointed out by Ioka et al. (2016), this two-step injection scenario needs an exotic behavior: the magnetic field should be initially large, resulting in a fast energy injection for a short duration, and then it may decay rapidly between the explosive injection and continuous injection.

Second, the initial rotational energy of a magnetar with an initial period \(P_0\) is \(\frac{1}{2}I\Omega_0^2 \approx 2 \times 10^{52}(I/10^{45}\text{ g cm}^2)(P_0/1\text{ ms})^{-2}\) erg. Here \(I\) is the moment of inertia of the magnetar and \(\Omega_0\) is its initial angular velocity. If \(P_0 = 1\)–\(5\) ms, the initial rotational energy is \(\sim (1\text{--}20) \times 10^{51}\) erg. Calculations (Kasen & Bildsten 2010; Woosley 2010; Wang et al. 2017b) have indicated that a fraction of the initial rotational energy of a magnetar would be converted to the KE of SNe.\(^{11}\) This huge amount of energy and its acceleration effect cannot be neglected.

\(^{11}\) For example, Woosley (2010) demonstrated that a magnetar with \(P_0 = 4.5\) ms and \(B_0 = 1 \times 10^8\) G would convert 40% of its initial rotational energy to the KE of the SN ejecta.
Table 3: Derived Physical Parameters

| SN Name         | $E_{B0}$a (10^{51} erg) | $E_{K0}$b (10^{51} erg) | $\eta^c$ | $(P_0, B_0)$ (ms, 10^{15} G) |
|----------------|-------------------------|--------------------------|----------|-------------------------------|
| DES13S2cm      | 4.55                    | 0.65                     | 0.89     | (5.5, 1.8)                    |
| DES14X3ha      | 45.1                    | 11.8                     | 0.27     | (1.3, 0.2)                    |
| Gaia16udpl     | 1.99                    | 3.77                     | 0.46     | (2.1, 2.2)                    |
| LSQ12ddf       | 0.1–0.43                | 10.92                    | 0.97     | (1.3, 5.5)                    |
| LSQ14mo        | 2.74                    | 2.14                     | 0.86     | (3.0, 6.9)                    |
| PS1-10wh       | 1.08                    | 3.15                     | 0.39     | (2.5, 0.5)                    |
| PS1-10bjz      | 0.22                    | 13.25                    | 0.97     | (1.2, 7.8)                    |
| PS1-11ap       | 0.1–0.45                | 1.30                     | 0.53     | (3.9, 2.1)                    |
| PS1-14bj       | 0.22                    | 2.81                     | 0.23     | (2.7, 0.4)                    |
| PTF10g6i       | 0.1–0.12                | 0.28                     | 0.27     | (8.3, 3.0)                    |
| PTF11rks       | 1.37                    | 0.42                     | 0.68     | (6.9, 8.8)                    |
| PTF12dam       | 0.1–0.39                | 2.76                     | 0.38     | (2.7, 0.8)                    |
| SN 2010gx      | 1.38                    | 11.82                    | 0.97     | (1.3, 8.5)                    |
| SN 2011ke      | 0.13                    | 2.92                     | 0.90     | (2.6, 7.1)                    |
| SN 2011kf      | 0.1–0.17                | 4.49                     | 0.80     | (2.1, 5.2)                    |
| SN 2012l       | 0.1–0.12                | 0.57                     | 0.52     | (5.9, 4.6)                    |
| SN 2013dg      | 0.1–0.12                | 1.03                     | 0.19     | (4.4, 1.2)                    |
| SN 2015bn      | 2.80                    | 3.87                     | 0.20     | (2.3, 0.5)                    |
| SSS 120810     | 2.12                    | 3.24                     | 0.83     | (2.5, 3.7)                    |

Notes.

a $E_{B0}$ is the initial kinetic energy of the SLSNe, and its lower limit has been set to be $1 \times 10^{50}$ erg.

b $E_{B0} = 2 \times 10^{52} (B_0/1 \text{ ms})^{-2}$ erg is the initial rotational energy of the magnetars proposed to power the SLSNe.

c $\eta$ is the accumulative fraction of the rotational energy of the magnetar converted to the kinetic energy of these SLSNe.

Our modeling based on the magnetar-powered model (Wang et al. 2017b) can simultaneously solve these two problems by taking into account the acceleration effect of the magnetar wind. We find that ~19%–97% of the initial rotational energy of the magnetars has been converted to the KE of the ejecta (see Table 3 and Figure 6 for some of these SLSNe) and the initial KEs of 15 SLSNe in our sample are smaller than $2.5 \times 10^{51}$ erg (see Table 3) provided by the neutrino-driven mechanism for CCSNe. The additional KE is provided by the magnetar wind that accelerates the ejecta.

Besides LSQ14mo, SN 2015bn and DES13S2cm have initial KEs (slightly) larger than ~$2.5 \times 10^{51}$ erg, but the initial KEs of these SLSNe can be halved to be ~$1.37 \times 10^{51}$, ~$1.41 \times 10^{51}$, and ~$2.28 \times 10^{51}$ erg if the value of $\kappa$ doubled ($\kappa = 0.2 \text{ cm}^2 \text{ g}^{-1}$), so that their ejecta masses can be halved. Therefore, these three SLSNe can also be explained by the magnetar model. The only SLSN whose KE cannot be explained by the magnetar-powered model is DES14X3ta, since its initial KE is $4.51 \times 10^{52}$ erg (if $\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}$) or $2.25 \times 10^{52}$ erg (if $\kappa = 0.2 \text{ cm}^2 \text{ g}^{-1}$), significantly larger than what can be provided by the neutrinos.

All in all, in our model, the neutrinos provide the initial KE of the ejecta, and the magnetar accelerates the ejecta so that they have large final KE ($> 5 \times 10^{53}$ erg). Thus, the difficulty of explaining the origin of the KEs of the SLSNe can be solved by taking into account the acceleration effect.12

Figure 7 shows the conversion fraction $\eta$ versus magnetic strength $B_\rho$. The correlation coefficient between these two quantities is $R = 0.715$, which means that larger $B_\rho$ results in a larger $\eta$. Wang et al. (2016c) demonstrated that the conversion fraction $\eta$ is high if the spin-down timescale of the magnetar is short compared to the diffusion timescale. It is therefore expected that the stronger $B_\rho$, the higher $\eta$ tends to be, although the other factors, e.g., $M_a$ and $P_0$, will cause some scatters in this relation.

If $B_\rho$ is increased further to $\sim 10^{16}$ G, we can expect that most of the magnetar’s rotational energy will be converted to the ejecta’s KE and the SNe will become dimmer. This is precisely what is seen for broad-lined Type Ic SNe (SN 1c-BL) by Wang et al. (2016b), who showed evidence that SN 1c-BL SN 1998bw and SN 2002ap were powered by magnetars (Wang et al. 2017b). This implies a continuous spectrum of magnetar-powered SNe.

The inferred gamma-ray opacity $\kappa_\gamma$ is ~0.01–0.82 cm$^2$ g$^{-1}$. Kotera et al. (2013) have demonstrated that the values of $\kappa_\gamma$ must be between approximately 0.01 and 0.2 cm$^2$ g$^{-1}$ if the emission is dominated by gamma photons and between approximately 0.2 and 10 cm$^2$ g$^{-1}$ if the emission is dominated by X-ray photons. In our sample, the values of $\kappa_\gamma$ of PTF12dam and SSS 120810 reach the lower limit, ~0.01 cm$^2$ g$^{-1}$ proposed by the theoretical prediction (see also Chen et al. 2015, for PTF12dam), suggesting that the energy of the gamma-ray radiation from the magnetars associated with these SLSNe must be higher than $3 \times 10^7$ eV = 30 MeV. Such high-energy photons from magnetars have already been observed (Hester 2008; Bübler & Blandford 2014) and can be explained by theoretical modelings (Metzger et al. 2014; Murase et al. 2015; Wang et al. 2016a).

For SLSNe in Figure 2, bolometric luminosity ($L$) and temperature ($T$) evolution can be well fitted, but the evolution of photospheric velocity ($v_{\text{ph}}$) cannot be fitted. This is strange since $L = 4 \pi \sigma T^4 R_{\text{ph}}^2 = 4 \pi \sigma T^4 \left(\int_{v_{\text{ph}}}^{r_{\text{max}}} v_{\text{ph}} dt\right)^2$ ($R_{\text{ph}} = \int_{v_{\text{ph}}}^{r_{\text{max}}} v_{\text{ph}} dt$ is the photospheric radius). The reason for this might be that the error bars of the observational data are too small. Observationally, the velocities inferred from different elements are rather different (see, e.g., Figure 7 of Taddia et al. 2016), so the error bars of the velocity data might be larger than those presented in Figure 2 but, see Liu & Modjaz (2016) for an alternative suggestion. To clarify this issue, more dedicated studies are required.

Some of the SLSNe in Figure 3 show flattening (SN 2011ke, SN 2015bn, PS1-11ap, PS1-14bj) in the late-time temperature evolution. This flattening may be caused by recombination, which is not considered in our adopted model. The most extreme case is PS1-14bj, whose temperature evolution is rather flat at the very beginning, and even slightly increasing with time. Another peculiar case is DES14X3ta, whose temperature evolution is a typical in the SN sample. We note that the SLSNe mentioned above (PS1-14bj, SN 2015bn, and DES14X3ta) are among the four SLSNe that are not well fitted by our model. These peculiar SLSNe deserve further investigation. The large reduced $\chi^2$ of SN 2015bn (among the four largest reduced $\chi^2$), on the other hand, is caused by the small errors in temperature measurement because its light-curve and velocity fitting quality is similar to that of PTF11rks.

5. Conclusions

Detailed studies of SLSNe in the past decade have revealed many important observational properties and given some crucial clues to understanding the energy-source models and the explosion mechanisms of SLSNe. In the past several years, most SLSNe discovered have been Type I, whose light curves and spectra are diverse and complex (e.g., Inserra et al. 2017).

Using the magnetar-powered and the MCMC approach, we fit the light curves, temperature evolution, and photospheric

\[ \text{Equation 1} \]

\[ \text{Equation 2} \]
velocity evolution of 19 SLSNe I. We get rather good fits for seven events ($\chi^2$/dof = 0.24–0.96) and good fits for another seven events ($\chi^2$/dof = 1.37–3.13), suggesting that these SLSNe can be explained by the magnetar model. Five events cannot be well fitted by this model ($\chi^2$/dof = 4.32–6.83), suggesting that these four events must be further studied.

The parameters determined by the MCMC code are as follows. The values of the initial period of the magnetars that

Figure 5. Distributions of the initial stellar periods $P_0$, magnetic strength $B_p$, ejecta masses $M_{ej}$, initial scale velocities of the ejecta $v_{sc}$, gamma-ray opacity $\kappa_{\gamma}$, initial kinetic energy of the ejecta $E_{K0}$, and the accumulative fraction of the rotational energy of the magnetar converted to the kinetic energy $\eta$ in the modeling of the sample.
supposedly power these SLSNe are 1.2–8.3 ms, the values of the magnetic strength of the magnetars are \((0.2\,\text{–}\,8.8) \times 10^{14} \, \text{G}\), the masses of the ejecta of these SLSNe are \(1\,\text{–}\,27.6 \, M_\odot\), and the gamma-ray opacities are \(0.01\,\text{–}\,0.82 \, \text{cm}^2 \, \text{g}^{-1}\).

More importantly, we take into account the acceleration effect and let the initial velocity of the ejecta be a free parameter, and we find that the initial KEs of most SLSNe in our sample are (significantly) smaller than the upper limit \((\sim 2.5 \times 10^{51} \, \text{erg})\) of the KEs provided by the neutrino-driven mechanism for CCSNe, indicating that our modelings are self-consistent and do not need any exotic assumption (e.g., two-step injections from the magnetars) to explain the origin of the ejecta kinetic energy of these SLSNe.

Our modeling shows that \(\sim 19\%\,\text{–}\,97\%\) of the initial rotational energy of the magnetars is converted to the KE of the SN ejecta. This acceleration effect is especially important in the SLSNe that
require magnetars with initial periods $P_0 \sim 1-5$ ms, since the initial rotational energy of these magnetars is ~$(1-20) \times 10^{51}$ erg and would convert ~$(0.2-20) \times 10^{51}$ erg to KE of the SLSN ejecta.

By combining these two results, we demonstrate that the KE acquired from the rotational energy dissipated via magnetic dipole radiation can naturally provide a considerable amount of the KE for the SN ejecta, and the difficulty of explaining the KEs of the SLSNe, which are usually (significantly) larger than $2 \times 10^{51}$ erg, can be solved.

Understanding the nature of SLSNe is one of the most challenging questions in astrophysics. Their explosion mechanisms and energy sources are still ambiguous. Our results provide some new and important clues related to these problems. To clarify these important issues, more observations and theoretical work are needed.

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