Stripped-envelope supernova light-curve bumps caused by variable thermal energy injection from magnetar spin down

Takashi J. Moriya,1,2 Kohta Murase,3,4,5,6 Kazumi Kashiyama,7,8 and Sergei I. Blinnikov9,10

1National Astronomical Observatory of Japan, National Institutes of Natural Sciences, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
2School of Physics and Astronomy, Faculty of Science, Monash University, Clayton, Victoria 3800, Australia
3Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
4Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
5Center for Multimessenger Astrophysics, Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
6Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto University, Sakyo, Kyoto 606-8502, Japan
7Research Center for the Early Universe, Graduate School of Science, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
8Department of Physics, Graduate School of Science, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
9NRC Kurchatov Institute, 123182 Moscow, Russia
10Dukhov Automatics Research Institute (VNIIA), 127055 Moscow, Russia

ABSTRACT

Luminosity evolution of some stripped-envelope supernovae such as superluminous supernovae is difficult to be explained by the canonical $^{56}$Ni nuclear decay heating. A popular alternative heating source is rapid spin down of strongly-magnetized rapidly-rotating neutron stars (magnetars) and it has been shown that magnetar spin down can explain luminosity evolution of superluminous supernovae. Recent observations have indicated that superluminous supernovae often have bumpy light curves with multiple luminosity peaks. The cause of bumpy light curves is still unknown. In this study, we investigate the possibility that the light-curve bumps are caused by variabilities in the thermal energy injection from magnetar spin down. We find that a temporal increase in the thermal energy injection can lead to multiple luminosity peaks. The multiple luminosity peaks caused by the variable thermal energy injection is found to be accompanied by significant photospheric temperature increase, and photospheric radii are not significantly changed. We show that the bumpy light curves of SN 2015bn and SN 2019stc can be reproduced by temporarily increasing magnetar spin-down energy input by a factor of 2 – 3 for 5 – 20 days. However, not all the light-curve bumps are accompanied by the clear photospheric temperature increase as predicted by our synthetic models. In particular, the secondary light-curve bump of SN 2019stc is accompanied by a temporal increase in photospheric radii rather than temperature, which is not seen in our synthetic models. We, therefore, conclude that not all the light-curve bumps observed in luminous supernovae are caused by the variable thermal energy injection from magnetar spin down and some bumps are likely caused by a different mechanism. Our study demonstrates the importance of photosphere information to identify the cause of the bumpy light curves.

Key words: supernovae: general – supernovae: individual: SN 2015bn, SN 2019stc

1 INTRODUCTION

Supernovae (SNe) are explosions of stars that can be as luminous as galaxies. There are several heating mechanisms that make SNe luminous. The major heating source of stripped-envelope SNe, which are explosions of stripped stars with little or no hydrogen-rich envelopes, is considered to be the nuclear decay energy of the radioactive $^{56}$Ni synthesized during their explosions (Pankey 1962; Arnett 1982). However, recent transient surveys are starting to discover SNe that are difficult to be powered by the $^{56}$Ni decay heating (Kasen 2017). For example, the luminosity decline of fast blue optical transients (FBOTs, see Inseria 2019 for a recent review) is much faster than that expected from the $^{56}$Ni decay heating (Ho et al. 2021, and references therein). Another example is superluminous SNe (SLSNe, Quimby et al. 2011) which sometimes require more than 10 $M_\odot$ of $^{56}$Ni to explain their peak luminosity (e.g., Nicholl et al. 2016a; Umeda & Nomoto 2008). SLSNe usually do not show observational signatures expected when a large amount of $^{56}$Ni is produced (e.g., Dessart et al. 2012; Jerkstrand et al. 2016; Mazzali et al. 2019). Thus, their luminosity source is not considered to be the $^{56}$Ni decay heating (e.g., Moriya et al. 2018a, for a review). It has also been suggested that some luminous stripped-envelope SNe may not be powered by the $^{56}$Ni heating even if they are not as luminous as SLSNe (e.g., Kashiyama et al. 2016; Afariardchi et al. 2021; Sollerman et al. 2021).

There are several alternative heat sources to account for the stripped-envelope SNe whose luminosity evolution cannot be explained by the canonical $^{56}$Ni heating. One is the interaction between SN ejecta and dense circumstellar matter (CSM, e.g., Sorokina et al. 2016). When SN ejecta hit a dense CSM, the kinetic energy of the
SN ejecta can be efficiently converted to thermal energy that can provide additional heat to illuminate SNe. Indeed, some stripped-envelope SNe such as Type Ibn and Type Icn SNe show observational signatures of dense CSM surrounding the SN ejecta (e.g., Pastorello et al. 2007; Ben-Ami et al. 2014; Moriya & Maeda 2016; Hosseinzadeh et al. 2017; Gangopadhyay et al. 2020; Fraser et al. 2021; Perley et al. 2021; Gal-Yam et al. 2021; Maeda & Moriya 2022).

Another possible alternative heat source is a compact central remnant formed during a SN explosion. A popular mechanism of this kind is rapid spin down of strongly-magnetized rapidly-rotating neutron stars (Ostriker & Gunn 1971; Gaffet 1977; Maeda et al. 2007; Kasen & Bildsten 2010; Woosley 2010). Such a neutron star is often called a “magnetar” in luminous SN studies. The huge rotational energy of magnetars can be released in a spin-down timescale of less than 100 days if their magnetic fields are more than \( \sim 10^{13} \) G, making SNe as luminous as SLSNe (e.g., Barkov & Komissarov 2011; Inserra et al. 2013; Metzger et al. 2015; Nicholl et al. 2017). Even if a black hole is formed at the center, alternatively, accretion towards the central black hole can be a heating source to make SNe luminous (e.g., Dexter & Kasen 2013; Moriya et al. 2018b).

Most stripped-envelope SNe have been characterized by a single peaked light curves (LCs) and their luminosity evolution is usually reproduced by assuming a single heating source. However, it is starting to be realized that some stripped-envelope SN LCs have bumpy structure with multiple luminosity peaks (e.g., Maeda et al. 2007; Roy et al. 2016; Yan et al. 2017, 2020; Gómez et al. 2021; Prentice et al. 2021). Especially, SLSNe are suggested to have bumpy LCs generally (Hosseinzadeh et al. 2021; Chen et al. 2022a,b). Even if the LC bump does not clearly exist, some extra luminosity contribution is suggested to be required to explain spectral properties of some SLSNe (e.g., Chen et al. 2017). The origin of the multiple luminosity peaks is still unknown. It is often assumed that each bump is caused by a different heating source (e.g., Li et al. 2020). For instance, a combination of the \( 56\text{Ni} \) heating and the magnetar spin-down heating is considered for the double peaked Type Ib SN 2005bf (Maeda et al. 2007). The combination of the CSM interaction and magnetar spin-down heating is also considered to explain multiple peaks in SLSN LCs (e.g., Chatzopoulos et al. 2016; Li et al. 2020).

While it is possible that several heating mechanisms play a role at the same time, it is also possible that multiple luminosity peaks are caused by a variation in a single energy source. It has been shown that luminosity variations can be caused if there are several shell structures in dense CSM (Liu et al. 2018). Whenever SN ejecta hit a shell, a temporal increase in luminosity causing a bumpy LC occurs. As we discuss in this paper, it is also possible that central energy injection from magnetar spin down is variable. However, the magnetar spin-down energy release is usually assumed to be a smooth decay and few studies consider the effect of variable magnetar spin-down energy inputs on LCs of stripped-envelope SNe (e.g., Kasen et al. 2016; Chugai & Utrobin 2021). In this paper, we investigate the effects of variable magnetar spin-down energy injection on photometric properties of stripped-envelope SNe to identify their expected observational signatures.

The rest of this paper is organized as follows. We first introduce the thermal energy inputs from magnetar spin down and possible physical mechanisms causing their variabilities in Section 2. In Section 3, we perform numerical LC modeling of SLSNe with variable thermal energy injection from magnetar spin down in order to clarify their effects on photometric properties. We compare our models with SNe with bumpy LCs to discuss if the bumpy LCs can be explained by variable energy injection in Section 4. The conclusion of this paper is summarized in Section 5.

2 VARIABLE THERMAL ENERGY INJECTION FROM MAGNETAR SPIN DOWN

We assume that the spin down of magnetars powering SNe is mainly caused by a vacuum dipole magnetic field\(^1\) as often assumed in SN modeling with magnetar spin down. Then, the spin-down rate (\( \dot{E}_{\text{rot}} \)) of magnetars is expressed as

\[
\dot{E}_{\text{rot}}(t) = \frac{E_{\text{rot,0}}}{t_{\text{sd}}} \left(1 + \frac{t}{t_{\text{sd}}}\right)^{-2},
\]

where \( t \) is time, \( E_{\text{rot,0}} \) is the initial rotational energy of a magnetar, and \( t_{\text{sd}} \) is the spin-down time. Given a dipole magnetic field (\( B_p \)) and an initial spin period (\( P_0 \)) of the magnetar, \( E_{\text{rot,0}} \) and \( t_{\text{sd}} \) can be expressed as

\[
E_{\text{rot,0}} = \frac{1}{2} I \left(\frac{2\pi}{P_0}\right)^2 = 2 \times 10^{52} \left(\frac{P_0}{1 \text{ ms}}\right)^2 \text{ erg},
\]

and

\[
t_{\text{sd}} = \frac{3L_{\text{th}}^2 P_0^2}{4\pi^2 B_p^2 R^6 \sin^2 \alpha} \approx 4 \times 10^5 \left(\frac{P_0}{1 \text{ ms}}\right)^2 \left(\frac{B_p}{10^{15} \text{ G}}\right)^2 \text{ sec},
\]

respectively, where \( L \approx 10^{45} \) g cm\(^2\) s\(^{-1}\) is the magnetar moment of inertia, \( c \) is the speed of light, \( R \approx 10 \) km is the magnetar radius, and \( \alpha \) is the angle between the magnetic and rotation axes. We set \( \alpha = 45^\circ \) in Eq. (3).

A fraction of spin-down energy is thermalized to make SNe bright. This fraction is, however, uncertain. Many SLSN studies assume that all the spin-down energy is thermalized to power SLSNe. However, this is not justified in light of physics of pulsar wind nebulae. Most of the spin-down energy should be extracted as Poyting-dominated outflows (e.g., Goldreich & Julian 1969). The observations of Galactic pulsar wind nebulae suggest that a significant fraction must be dissipated around the termination shock as non-thermal energy (e.g., Kennel & Coroniti 1984a,b). Thus, other studies assume that the spin-down energy is released as non-thermal electrons and calculate photon spectra, taking their opacity into account to estimate the fraction of high-energy photons to be thermalized (e.g., Kotera et al. 2013; Metzger et al. 2014; Murase et al. 2015; Wang et al. 2015; Kashiyama et al. 2016; Nicholl et al. 2017; Vurm & Metzger 2021). In this study, we adopt a simplified parameterization to convert the spin-down energy to thermal energy powering SN LCs. Namely, we simply assume that a fraction \( \varepsilon_{\text{th}} \) of spin-down energy is thermalized and the thermal energy input from magnetar spin down is expressed as

\[
L_{\text{mag}}(t) = \varepsilon_{\text{th}}(t) \dot{E}_{\text{rot}}(t).
\]

The aim of this paper is to investigate the effect of variable thermal energy injection from magnetar spin down. The effect of variable thermal energy injection is taken into account by changing \( \varepsilon_{\text{th}}(t) \) in the following sections. Several mechanisms that may temporarily change \( \varepsilon_{\text{th}}(t) \) can be considered.

The thermalization efficiency \( \varepsilon_{\text{th}}(t) \) can be interpreted to have two

---

\(^1\) Our discussion and conclusions do not change even if we assume a force-free magnetic field (Contopoulos et al. 1999; Spitkovsky 2006; Gruzinov 2007), although the estimated dipole magnetic field and initial spin period become different.
components, i.e., \( e_{th}(t) = e_c(t) f_{\text{dep}, \gamma}(t) \). The first component \( e_c(t) \) is the conversion efficiency from the spin-down energy to electron-positron pairs that form pulsar winds. The electron-positron pairs are further accelerated to high energies and release high-energy photons via synchrotron and inverse-Compton emission mechanisms. The gamma rays will be absorbed in the SN ejecta at early times. The second component \( f_{\text{dep}, \gamma}(t) \) is the fraction of high-energy photons that will be absorbed and thermalized in the SN ejecta. The factor \( f_{\text{dep}, \gamma}(t) \) can be regarded as the effect of opacity.

The conversion efficiency to the nonthermal particle energy, \( e_c(t) \), is considered to be close to unity in Galactic pulsar wind nebulae (e.g., Kasen & Coroniti 1984a,b; Tanaka & Takahara 2011). However, for newborn magnetars with the magnetization parameter that is much larger than unity, most spin-down energy may remain as the magnetic energy at the termination shock (e.g., Arons 2012; Murase et al. 2014). In such a case, \( e_c(t) \) may be much lower than unity, but could temporarily increase due to magnetic dissipation in the nebula (e.g., Porth et al. 2014).

The absorption fraction \( f_{\text{dep}, \gamma}(t) \) can also change with time. For example, pair multiplicity injected into magnetar winds might be temporarily increased by, e.g., a flaring activity of magnetars. The temporal increase in pair multiplicity leads to the temporal reduction in injected particle energy and, therefore, the temporal energy reduction in photons radiated from high-energy particles. Because opacity of high-energy photons strongly depends on photon energy (e.g., Kotera et al. 2013; Murase et al. 2015; Murase et al. 2021; Badjin 2016; Vurm & Metzger 2021), the temporal change in the energy of injected photons can lead to a temporal change in \( f_{\text{dep}, \gamma}(t) \). The factor \( f_{\text{dep}, \gamma}(t) \) may increase or decrease depending on the original spectral energy distributions.

Effects of variable thermal energy injection from magnetar spin down due to inefficient thermalization by the reduction in \( e_c(t) \) and \( f_{\text{dep}, \gamma}(t) \) was previously studied by Kasen et al. (2016). They considered the effect of inefficient thermalization shortly after the magnetar formation in order to explain precursors sometimes observed in SLSNe (Nicholl & Smartt 2016; Angus et al. 2019). In this study, we focus on variable thermal energy injection at later phases, mostly after the main luminosity peak.

In this work, we change \( e_{th}(t) \) to investigate the effect of variable thermal energy injection from magnetar spin-down. However, we can also consider other ways to change the spin-down energy injection rate with time. For example, the variable magnetar energy injection can be realized by changing the angle between the magnetic and rotation axes (\( \alpha \)). The angle determines the spin-down time (Eq. 3) and a temporal change in the angle can result in a temporal variation in the magnetar energy injection rate. The angle could naturally get larger because having a larger angle leads to a lower moment of inertia and, therefore, a lower energy state. In this case, the thermalization rate does not need to change to have a variable energy injection.

Another similar mechanism to cause the variable magnetar spin-down energy injection is to make a variation in the magnetar spin. The fallback accretion towards the central magnetar can provide angular momentum that accelerates the rotation of the magnetar (e.g., Barkov & Komissarov 2011). The spin-up of the magnetar results in the increase of the energy injection. This variation is, again, not a simple increase in \( e_{th} \). If the fallback accretion occurs intermittently, the energy injection variation can be observed several times.

### 3 EFFECT OF VARIABLE THERMAL ENERGY INJECTION ON SLSN PROPERTIES

We investigate the effects of the variable thermal energy injection from magnetar spin down discussed so far on observational properties of SLSNe in this section.

#### 3.1 Methods

In order to quantify the effect of the variable magnetar energy injection on SLSN observational properties, we perform numerical LC calculations of SLSNe powered by magnetar spin down. We use one-dimensional multi-frequency radiation hydrodynamics code STELLA (Blinnikov et al. 1998, 2000, 2006) for this purpose. Briefly, STELLA implicitly calculates time-dependent equations of the angular moments of intensity averaged over a frequency bin using the variable Eddington method. In a standard setup, 100 frequency bins are set, but see also Kasen et al. 2016). Nevertheless, LC bumps from variable magnetar thermal energy injection

**MNRAS 000, 1–9 (2022)**
Figure 1. Bolometric LCs with temporal magnetar thermal energy injection increase by a factor of 10 starting at 50 days, which is 10 days after the bolometric LC peak of the reference model (dashed line) with the constant $\varepsilon_{eb} = 0.1$ at all times.

Figure 2. Bolometric LCs with temporal magnetar thermal energy injection increase starting at 50 days with the same $\varepsilon_{eb} \Delta t = 3$. The models with $\varepsilon_{eb} > 1$ are shown for demonstration. The reference model (dashed line) has the constant $\varepsilon_{eb} = 0.1$ at all times.

Figure 3. Photospheric temperature (top), radius (middle), and velocity (bottom) evolution of the models in which the magnetar energy conversion efficiency, which is set as $\varepsilon_{eb} = 0.1$ at all times in the reference model (dashed lines), is temporarily increased by a factor of 10 ($\varepsilon_{eb} = 1$). The bolometric LCs of the models are presented in Fig. 1. The dot-dashed lines in the middle and bottom panels show the location of the innermost layer in our numerical calculations that corresponds to the termination shock.

3.2 Results

3.2.1 Reference model

We first introduce our reference model in which we do not include variability in the magnetar energy injection, i.e., $\varepsilon_{eb} = 0.1$ at all time in Eq. (4). We adopt the 5 $M_\odot$ ejecta model and the explosion energy is set to $5 \times 10^{51}$ erg in all the models. Assuming the electron
scattering opacity of 0.2 cm$^2$ g$^{-1}$, the corresponding diffusion time of the ejecta is 32 days.

We set $B_p = 3 \times 10^{13}$ G and $P_0 = 1$ ms, which corresponds to $E_{\text{magnar}} = 2 \times 10^{52}$ erg and $t_{\text{dd}} = 52$ days. The bolometric LC from the reference model is presented in Fig. 1 with a dashed line. It has the rise time of 40 days and the peak bolometric luminosity of $1.4 \times 10^{44}$ erg s$^{-1}$. Photospheric properties of the reference model can be found in Fig. 3. We introduce variable thermal energy injection to this model and discuss its effect compared to this reference model from next section.

3.2.2 Temporal energy increase after the LC peak

We first temporarily increase $\varepsilon_{\text{th}}$ from 50 days, which is 10 days after the bolometric LC peak. Fig. 1 shows the changes in the bolometric LCs when we increase $\varepsilon_{\text{th}}$ by a factor of 10 at 50 – 50.1 days ($\Delta t = 0.1$ days), 50 – 50.3 days ($\Delta t = 0.3$ days), 50 – 51 days ($\Delta t = 1$ day), 50 – 53 days ($\Delta t = 3$ days), and 50 – 60 days ($\Delta t = 10$ days). Here, $\Delta t$ is the duration of the temporal $\varepsilon_{\text{th}}$ change. We start to see the clear second bump caused by the increased energy injection if the energy increase is kept for more than 1 day.

Fig. 2 shows the bolometric LCs with the temporal $\varepsilon_{\text{th}}$ increase from 50 days with the constant $\varepsilon_{\text{th}}\Delta t = 3$. We can find that the effect of the temporal $\varepsilon_{\text{th}}$ increase in these models is the same when $\Delta t$ is so small that the diffusion in the ejecta determines the subsequent bolometric LC properties. Then, the peak time of the second bump increases as $\Delta t$ increases.

Fig. 3 shows the photospheric temperature ($T_{\text{ph}}$), radius ($R_{\text{ph}}$), and velocity of the models in which $\varepsilon_{\text{th}}$ is temporarily increased by a factor of 10. The dot-dashed lines in the panels of the photospheric radius and velocity show the location of the innermost layer where thermal energy from the magnetar spin-down is injected. It corresponds to the termination shock in our calculations. In the reference model, the ejecta cool adiabatically after the shock breakout and the photospheric temperature keeps decreasing. Then, the photospheric temperature increases from around 7 days as the thermal energy injection from the magnetar spin-down heats the ejecta. The SN ejecta become optically thin when the dot-dashed line matches the photospheric radius in Fig. 3 which occurs at 120 days after the explosion. At this moment, the photosphere no longer exists and the photospheric information shown in the figure is unphysical. Especially, the photospheric temperature increase from 100 days to 120 days is an artifact caused by the proximity of the photosphere and the location of the thermal energy injection.

Comparing the photosphere information in Fig. 3 with the bolometric LCs presented in Fig. 1, we can find that there is significant increase in photospheric temperature during the temporal $\varepsilon_{\text{th}}$ increase, while changes in photospheric radii and, therefore, velocity,
are minor. This shows that the temperature increase is the major cause of the bolometric luminosity increase ($4\pi R^2 \sigma T^4$, where $\sigma$ is the Stefan–Boltzmann constant) when a second LC peak appears due to the temporal increase in the central thermal energy injection. The temporal increase of the injected thermal energy leads to the temperature increase of the ejecta. However, the inner temperature growth is not large enough to change the ionization state of the ejecta at around the photosphere. Thus, the photospheric radius is not strongly altered by the inner temperature growth and the photospheric temperature increase is mainly observed.

3.2.3 Temporal energy variations at different epochs

In the previous section, we presented the models in which $e_{\text{th}}$ is temporarily increased after the bolometric LC peak of the reference model. Here we show the models in which $e_{\text{th}}$ is temporarily changed at various times.

Fig. 4 shows the bolometric LC models in which $e_{\text{th}}$ is temporarily changed from the original value of $e_{\text{th}} = 0.1$ at various times. First, the bolometric LCs in the top panel of Fig. 4 are those with the temporal magnetar spin-down energy input increase by a factor of 10. We can find that the temporal energy increase before the bolometric LC peak at 40 days does not lead to multiple LC peaks. The rise time of bolometric LCs corresponds to the diffusion time of the ejecta. The thermal energy added before the bolometric LC peak simply diffuses out in the original diffusion timescale without making an additional peak in the bolometric LCs. When the energy increase occurs after the bolometric LC peak, a secondary bolometric LC peak can be observed. As discussed in the previous section, photospheric temperature is mainly affected by the additional energy input. Fig. 5 shows the photospheric temperature and $g - r$ color evolution of the models presented in the top panel of Fig. 4. We can find that the temporal photospheric temperature increase accompanied by the bolometric luminosity increase. The $g - r$ color becomes bluer by about 0.1 mag during the temporal luminosity increase.

The bottom panel of Fig. 4 shows the bolometric LC models in which the magnetar energy injection is temporarily reduced by a factor of 10. We do not find significant effects on the photometric properties when we reduce the energy injection temporarily.

4 COMPARISONS WITH OBSERVATIONS

We have shown the effects of temporal variations in injected thermal energy in magnetar-powered SN models. It is found that temporal injected energy increase after the bolometric LC peak can result in the temporal increase in luminosity. Photospheric temperature is significantly increased during the temporal luminosity increase, while the photospheric radius and velocity are less affected. In this section, we compare our models with the observational properties of luminous SNe with multiple luminosity peaks.

4.1 SN 2015bn

SN 2015bn is a SLSN known to have bumpy LCs as reported in Nicholl et al. (2016a,b). We take the bolometric LC and photospheric properties reported by Nicholl et al. (2016a) and compare them with our model with variable thermal energy injection from magnetar spin down. We use the s45 progenitor model having the ejecta mass of $11.6 \, M_\odot$ for this purpose. The progenitor model is exploded to have the explosion energy of $5 \times 10^{51}$ erg with a thermal bomb. Our reference model with the constant $e_{\text{th}} = 0.1$ has $B_0 = 2 \times 10^{13}$ G and $P_0 = 0.8$ ms, which corresponds to $E_{\text{rot},0} = 3.1 \times 10^{52}$ erg and $t_{\text{id}} = 75$ days. Other studies obtain different $B_0$ and $P_0$ because of different assumptions on $e_{\text{th}}$ and the spin-down formula (e.g., Nicholl et al. 2016a; Omand et al. 2018). The reference model has the rise time of 61 days and the peak bolometric luminosity of $1.6 \times 10^{44}$ erg s$^{-1}$. We temporarily change $e_{\text{th}}$ from the reference model to match the observed properties.

Figure 6. Bolometric LC (top), photospheric temperature (middle), and photospheric radius of SN 2015bn and their comparison with our synthetic models with temporal $e_{\text{th}}$ variations. The top panel also shows $e_{\text{th}}(t)$. The observational data are taken from Nicholl et al. (2016a). The photospheric radii keep increasing in the synthetic models even after the ejecta become optically thin, which is beyond the applicability of the models (Section 3.2.2).
LC bumps from variable magnetar thermal energy injection

We succeed in reproducing the two LC bumps observed in the bolometric LCs by introducing two phases of the temporal increase of $\varepsilon_{\text{th}}$. We first increase $\varepsilon_{\text{th}}$ by a factor of 2.5 from 65 days to 85 days to match the major bolometric LC peak at around 90 days. Then, increasing $\varepsilon_{\text{th}}$ by a factor of 3 from 115 days to 120 days enables us to account for the luminosity increase starting at 120 days. The extra thermal energy released during the temporal increase in $\varepsilon_{\text{th}}$ is $3.1 \times 10^{50}$ erg in 65–85 days and $6.3 \times 10^{50}$ erg in 115–120 days.

The luminosity increase in the synthetic model caused by the temporal increase in $\varepsilon_{\text{th}}$ is clearly accompanied by photospheric temperature increase as discussed in Section 3. The photospheric temperature of SN 2015bn estimated from the observations around the bolometric LC peak indeed show clear temporal increase in photospheric temperature (Fig. 6). On the other hand, the second LC bump starting from around 120 days does not have a clear photospheric temperature increase as in the previous LC peak. The observed photospheric radius has a slight increase during this bump which is not found in the synthetic model. Thus, the first bump causing the luminosity peak at around 90 days is consistent with the variable thermal energy injection from magnetar spin down, while it is difficult to conclude that the second bump is caused by the variable thermal energy injection.

4.2 SN 2019stc

SN 2019stc is a luminous Type Ic SN with the peak bolometric luminosity of around $4 \times 10^{43}$ erg s$^{-1}$ (Gomez et al. 2021). It is not as luminous as typical SLSNe, but the peak luminosity is difficult to reach by the canonical $^{56}$Ni heating, and it is suggested to be powered by magnetar spin down (Gomez et al. 2021). The bolometric LC of SN 2019stc has a clear secondary peak as shown in Fig. 7. We investigate if the secondary peak can be explained by the variable energy input from magnetar spin down. We adopt the same progenitor model as used for SN 2015bn in the previous section (s45 progenitor model). The explosion energy is set as $5 \times 10^{51}$ erg. Our models have $B_p = 7 \times 10^{13}$ B and $P_0 = 2.4$ ms. They correspond to $E_{\text{rot},0} = 3.5 \times 10^{51}$ erg and $t_{\text{sd}} = 55$ days. The reference model has a constant $\varepsilon_{\text{th}} = 0.1$ and we temporarily vary $\varepsilon_{\text{th}}$ to match the bolometric LC of SN 2019stc.

Fig. 7 shows the comparison between the observations and synthetic models. The first observed peak is matched by temporarily increasing $\varepsilon_{\text{th}}$ by a factor of 3 from 0 days to 25 days. As presented in Section 3, temporal increase of $\varepsilon_{\text{th}}$ starting before the bolometric LC peak of the reference model does not lead to multiple LC peaks but alters the first peak already seen in the reference model. The temporal $\varepsilon_{\text{th}}$ increase starting before the bolometric LC peak allows us to match the observed first peak well. Then, the secondary bolometric LC peak is reproduced by increasing $\varepsilon_{\text{th}}$ by a factor of 2 from 110 days to 130 days. The extra thermal energy released during the temporal increase in $\varepsilon_{\text{th}}$ is $2.2 \times 10^{50}$ erg at 0–25 days and $2.5 \times 10^{49}$ erg at 110–130 days. Chugai & Utrobin (2021) recently showed a similar model to increase the magnetar spin-down energy input to explain the secondary bolometric LC peak.

Interestingly, SN 2019stc does not show a clear increase in photospheric temperature during the secondary bolometric LC peak as shown in Fig. 7. The observed bolometric luminosity increase is mostly due to the increase in the photospheric radius. However, our models with temporal increase in thermal energy injection from magnetar spin down predict no significant increase in the photospheric radius as shown in Fig. 7. Therefore, we argue that the bumpy LC observed in SN 2019stc is not necessarily caused by variable thermal energy injection from magnetar spin down. Chugai & Utrobin (2021) concluded that the multiple LC peaks of SN 2019stc can be explained by increasing the magnetar energy input just by using LC information. Our results show that it is important to check photo-

Figure 7. Bolometric LC (top), photospheric temperature (middle), and photospheric radius of SN 2019stc and their comparison with our synthetic models with temporal $\varepsilon_{\text{th}}$ variations. The top panel also shows $\varepsilon_{\text{th}}(t)$. The observational data are taken from Gomez et al. (2021).
spheric properties to make constraints on the cause of the bumpy LCs.

4.3 Implications

We have compared the observational properties of SN 2015bn and SN 2019stc, which are luminous SNe with bumpy LCs, with our synthetic models with temporal variation in $e_{th}$ to see if the bumpy LCs can be explained by the variable thermal energy injection from magnetar spin down. We showed that the bumpy bolometric LCs of the two SNe can be reproduced by the temporal variability in the thermal energy injection by a factor of 2 – 3. The required timescale for the temporal injected thermal energy increase is ~ 1 – 10 days. This timescale can be comparable to the the thermalization timescale in the SN ejecta with the radius of around $10^{15}$ cm, given the high-energy photon optical depth of the order of 10 – 100. Because of the large required extra energy to make the LC bumps ($> 10^{49}$ erg), the temporal magnetic field energy release as observed in Galactic magnetars is not likely the cause of the LC bumps.

The bumpy LCs caused by the variable thermal energy injection are predicted to be accompanied by the significant photospheric temperature increase. While the first luminosity bump in SN 2015bn is observed to have the photospheric temperature increase during the LC bumps as predicted by the variable magnetar energy injection, SN 2019stc does not have the photospheric temperature increase as predicted by our synthetic models. The bumpy LC of SN 2019stc is accompanied by the significant photospheric radius increase which is not predicted in our models with variable thermal energy injection from magnetar spin down. We conclude that the variations in thermal energy injection do not explain all the bumpy LCs observed in luminous and superluminous SNe, and other mechanisms such as additional CSM interaction are also required to be considered.

5 CONCLUSIONS

We have investigated the effect of variable thermal energy injection from magnetar spin down on photometric properties of luminous SNe including SLSNe. We assumed that thermalization efficiency of magnetar spin down energy can change temporally and investigated their effects on the photometric properties. We showed that temporal increase in thermalization efficiency after the bolometric luminosity peak can result in bumpy LCs as observed in some luminous and superluminous SNe. We found that photospheric temperature is significantly increased during the LC bumps caused by the variable thermalization efficiency, while the photospheric radius is less affected.

We have found that the observed LC bumps in SN 2015bn and SN 2019stc can be reproduced by temporarily increasing the thermalization efficiency by a factor of 2 – 3 for 5 – 20 days. However, some observed LC bumps, especially those in SN 2019stc, are not accompanied by the photospheric temperature increase as clear as our synthetic models predict. Thus, we conclude that the bumpy LCs observed in luminous and superluminous SNe may not necessarily always originate from the variable thermalization of the magnetar spin-down energy. Several different mechanisms such as a CSM interaction could be active in making bumpy LCs in luminous and superluminous SNe.

ACKNOWLEDGEMENTS

The authors thank the Yukawa Institute for Theoretical Physics (YITP) at Kyoto University, where this work was initiated during the YITP workshop YITP-T-21-05 on "Extreme Outflows in Astrophysical Transients." We thank Matt Nicholl for providing the data of SN 2015bn and Sebastian Gomez for providing the data of SN 2019stc. T.J.M. is supported by the Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (JP18K13585, JP20H00174, JP21K13966, JP21H04997). This work of K.M. is supported by the NSF Grant No. AST-1908689, No. AST-2108466 and No. AST-2108467, and KAKENHI No. 20H01901 and No. 20H05852. The work by S.I.B. on SN1c studies is supported by RFBR-DFG project 21-52-12032 and on the code STELLA by grant RSF 19-12-00229. Numerical computations were in part carried out on PC cluster at Center for Computational Astrophysics (CfCA), National Astronomical Observatory of Japan.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Afsarian-Dachi N., Drout M. R., Khatami D. K., Matzner C. D., Moon D.-S., Ni Y. Q., 2021, ApJ, 918, 89
Agullera-Dena D. R., Langer N., Moriya T. J., Schootevmeijer A., 2018, ApJ, 858, 115
Angus C. R., et al., 2019, MNRAS, 487, 2215
Apan N. D., 1982, ApJ, 253, 785
Arons J., 2012, Space Sci. Rev., 173, 341
Badjin D. A., 2016, https://wwwmpa.mpa-garching.mpg.de/hydro/NucAstro/PDF_16/Badjin.pdf
Barkov M. V., Komissarov S. S. , 2011, MNRAS, 415, 944
Ben-Ami S., et al., 2014, ApJ, 785, 37
Blanchard P. K., Berger E., Nicholl M., Villar V. A., 2020, ApJ, 897, 114
Blinnikov S. I., Eastman R., Bartunov O. S., Popolitov V. A., Woosley S. E., 1998, ApJ, 496, 454
Blinnikov S., Lundqvist P., Bartunov O., Nomoto K., Iwamoto K., 2000, ApJ, 532, 1132
Blinnikov S. I., Röpke F. K., Sorokina E. I., Gieseler M., Reinecke M., Travaglio C., Hillebrandt W., Stritzinger M., 2006, A&A, 453, 229
Chatzopoulos E., Wheeler J. C., Vinko J., Nagy A. P., Wiggins B. K., Even W. P., 2016, ApJ, 828, 94
Chen T. W., et al., 2017, A&A, 602, A9
Chen Z. H., et al., 2022a, arXiv e-prints, p. arXiv:2202.02059
Chen Z. H., et al., 2022b, arXiv e-prints, p. arXiv:2202.02060
Chugai N. N., Urobin V. P., 2021, arXiv e-prints, p. arXiv:2112.07989
Contopoulos I., Kazanas D., Fendt C., 1999, ApJ, 511, 351
Dessart L., Hillier D. J., Waldman R., Blondin S., 2012, MNRAS, 426, L76
Dexter J., Kasen D., 2013, ApJ, 772, 30
Fraser et al., 2021, arXiv e-prints, p. arXiv:2108.07278
Gaffet B., 1977, ApJ, 216, 565
Gal-Yam A., et al., 2021, arXiv e-prints, p. arXiv:2111.12435
Gangopadhyay A., et al., 2020, ApJ, 889, 170
Goldreich P., Julian W. H., 1969, ApJ, 157, 869
Gomez S., Berger E., Hosseinzadeh G., Blanchard P. K., Nicholl M., Villar V. A., 2021, ApJ, 913, 143
Gruzinov A., 2007, ApJ, 667, L69
Ho A. Y. Q., et al., 2021, arXiv e-prints, p. arXiv:2105.08811
Hosseinzadeh G., et al., 2017, ApJ, 836, 158
Hosseinzadeh G., Berger E., Metzger B. D., Gomez S., Nicholl M., Blanchard P., 2021, arXiv e-prints, p. arXiv:2109.09743
