We perform a comprehensive study of the physical properties of SN 2018gk, which is a luminous Type Ib supernova (SN). We find that the early-time photospheric velocity varies from a larger value to a smaller one before the photosphere reaches a temperature floor. We generalize the photosphere modulus and fit the multiband light curves (LCs) of SN 2018gk. We find that the $^{56}$Ni mass model requires $\sim 0.90 M_\odot$ of $^{56}$Ni, which is larger than the derived ejecta mass ($\sim 0.10 M_\odot$). Alternatively, we use the magnetar plus $^{56}$Ni and the fallback plus $^{56}$Ni models to fit the LCs of SN 2018gk, finding that the two models can fit the LCs. We favor the magnetar plus $^{56}$Ni model since the parameters are rather reasonable ($M_{\text{ej}} = 1.65 M_\odot$, $M_{\text{Ni}} = 0.05 M_\odot$, which is smaller than the upper limit of the $^{56}$Ni mass that can be synthesized by neutrino-powered core-collapse SNe, $B = 6.52 \times 10^{14}$ G, which is comparable to magnetic fields in luminous and superluminous SNe studied in the literature, and $P_{\text{rot}} = 10.42$ ms, which is comparable to initial periods for luminous SNe), while the validity of the fallback plus $^{56}$Ni model depends on the accretion efficiency ($\eta$). Therefore, we suggest that SN 2018gk might be an Ib SNe powered mainly by a central engine. Finally, we confirm the near-IR excesses of the spectral energy distributions of SN 2018gk at some epochs and constrain the physical properties of the putative dust using the blackbody plus dust emission model.

Unified Astronomy Thesaurus concepts: Supernovae (1668); Type II supernovae (1731); Magnetars (992); Circumstellar dust (236)

1. Introduction

It is widely believed that a massive star whose zero-age main-sequence mass $M_{\text{ZAMS}} \gtrsim 8.0 M_\odot$ will explode as a core-collapse supernova (CCSN; Woosley et al. 2002), leaving a neutron star (NS) or black hole (BH). Most CCSNe can be classified into Types IIP, IIL, IIn, Ib, Ic according to their spectra and light curves (LCs) (Filippenko 1997). In the past two decades, some new subclasses of CCSNe, such as Ib and Icn, have been confirmed. In general, SNe Ib, Ic, IIb, Ibn, and Icn can be collectively referred to as stripped-envelope SNe (SESNe; Clocchiatti et al. 1996), since the hydrogen and/or helium envelopes of their progenitors have been partly or completely stripped.

The early-time spectra of SNe Ib show hydrogen absorption lines, while their late-time spectra do not show hydrogen lines, but show helium absorption lines (Filippenko 1988). These features make SNe Ib the transitional type between SNe II, whose spectra continue to show hydrogen absorption lines, and SNe Ib, whose spectra have helium absorption lines. It is suggested that the progenitors stars of SNe Ib lost most of their hydrogen envelopes through stellar winds and/or binary interactions (Podsiadlowski et al. 1992; Yoon et al. 2010, 2017; Sravan et al. 2019), leaving envelopes containing $\sim 0.1 M_\odot$ of hydrogen.

The peak absolute magnitudes ($M_{\text{peak}}$) of most SNe Ib are dimmer than $-19.0$ mag. However, a few SNe Ib are overluminous, with $M_{\text{peak}}$ brighter than $-19.0$ mag or even $-20.0$ mag, magnitudes that are between those of superluminous supernovae (SLSNe, $M_{\text{peak}} \lesssim -21$ mag, Gal-Yam 2012) and normal SNe.

For instance, $M_{\text{peak}}$ of SNe Ib PTF10hgi, DES14X2fna, and SN 2018gk (ASASSN-18am) are $\sim -20.42$ mag (g band, Inserra et al. 2013), $\sim -19.3$ mag (g band, Grayling et al. 2021), and $\sim -19.7$ mag (V band, Bose et al. 2021, hereafter B21), respectively.

This work focuses on the physical properties of SN 2018gk. SN 2018gk was discovered (Brimacombe et al. 2018) by the All-Sky Automated Survey for Supernovae (ASASSN; Shappee et al. 2014; Kochanek et al. 2017) on 2018 January 12.5 UT. The host galaxy of SN 2018gk is WISE J163554.27+400151.8, whose redshift $z$ is 0.031010 $\pm$ 0.000005 (SDSS Collaboration 2017). The spectral sequence of SN 2018gk indicates that it is an SN Ib. B21 find that its $M_{\text{peak}}$ in the V-band is $\approx -19.7$ mag, which is at least one magnitude brighter than those of most SNe Ib, and comparable to those of luminous SNe Ib PTF10hgi and DES14X2fna.

B21 construct the bolometric LC and use the radiative diffusion ($^{56}$Ni plus internal energy) model to fit it, finding that the required $^{56}$Ni mass $M_{\text{Ni}}$ is $\sim 0.4 M_\odot$. They also use the magnetar plus $^{56}$Ni model to fit the bolometric LC and find that the initial period ($P_{\text{rot}}$) and the magnetic field strength ($B$) of the magnetar are $\sim 1.2$ ms and $\sim 4 \times 10^{13}$ G, respectively. As pointed out by B21, the value of $B$ is higher than those of SLSNe I modeled by Nicholl et al. (2017), which are a few $10^{13}$ G to a few $10^{14}$ G. B21 suggest that the extreme value of $B$ is

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4 We note, however, that luminous SNe with $M_{\text{peak}}$ of $-20$ to $-21$ mag are also classified as SLSNe in some literature.

5 PTF10hgi had been classified as a Type Ic SLSN by Inserra et al. (2013), but Quimby et al. (2018) suggest that it is an SLSN Ib, since its spectrum shows clear evidence of hydrogen and helium.
Thus signification SN shock dynamics. Furthermore, B21 point out that the magnetar does not reduce \( M_{\text{Ni}} \) significantly since the \( 56\text{Ni} \) mass derived from the magnetar plus \( 56\text{Ni} \) model is \( \sim 0.3\ M_{\odot} \). The \( 56\text{Ni} \) masses derived from the two models are larger than the upper limit \( \sim 0.2\ M_{\odot} \) of the \( 56\text{Ni} \) mass that can be synthesized by the neutrino-power mechanism (Sukhbold et al. 2016; Ertl et al. 2020). Soker & Kaplan (2021) fit the \( V \)-band data of SN 2018gk using a two-component bipolar model. The photometry in all other bands has not been used.

Therefore, we suggest that the energy source of SN 2018gk is still elusive and deserves further study. In this paper, we research the energy source model, the physical parameters of the models, and the properties of the possible dust of SN 2018gk. In Section 2, we model the multiband LCs for SN 2018gk using three models (the \( 56\text{Ni} \) model, the magnetar plus \( 56\text{Ni} \) model, and the fallback plus \( 56\text{Ni} \) model). In Section 3, we study the near-infrared (NIR) excesses of SN 2018gk and constrain the physical properties of the putative dust. In Section 4, we discuss our results. We draw some conclusions in Section 5. Throughout the paper, we assume \( \Omega_{\text{m}} = 0.315 \), \( \Omega_{\Lambda} = 0.685 \), and \( H_0 = 67.3\ \text{km\ s}^{-1}\ \text{Mpc}^{-1} \) (Planck Collaboration 2014), and the values of the Milky Way reddening \( (E_B - V) \) from Schlafly & Finkbeiner (2011).

### 2. Modeling the Multiband Light Curves of SN 2018gk

B21 construct and fit the bolometric LC of SN 2018gk. It should be noted, however, that the upper limits at two very early epochs in the \( V \) and six data points in the \( V \) and \( g \) bands at four early epochs cannot be included in the constructed LC. Therefore, modeling the multiband LCs might yield more reliable results and place more stringent constraints on the physical properties of SN 2018gk.

The bolometric luminosity of powered SNe is (see, e.g., Arnett 1982; Chatzopoulos et al. 2012; Wang et al. 2015; Wang & Gan 2022)

\[
L_{\text{SN}}(t) = \frac{2}{\tau_m} e^{-t/\tau_m^2} \int_0^t e^{(t'-\tau_m^2/2)/\tau_m^2} L_{\text{input}}(t') dt',
\]

where \( \tau_m = (2\kappa M_{\text{ej}}/3\text{SN} v_{\text{ej}} c)^{1/2} \) is the diffusion timescale

(32 1 CF is the cutoff parameter; \( L_{\text{input}}(t) \) is the bolometric LC of SN 2018gk). It becomes

\[
\frac{L(t)}{L_\text{bol,SN}} = \frac{2}{\tau_m} e^{-t/\tau_m^2} \int_0^t e^{(t'-\tau_m^2/2)/\tau_m^2} L_{\text{input}}(t') dt',
\]

\[
F_v = \begin{cases} \frac{\lambda}{\lambda_{\text{CF}}} & \left(\frac{2\pi h v^3}{c^2}\right)(e^{h v/k_B T_{\text{ph}}} - 1)^{-1} \frac{R_{\text{ph}}^2}{D_L^2}, \\ \frac{2\pi h v^3}{c^2}(e^{h v/k_B T_{\text{ph}}} - 1)^{-1} \frac{R_{\text{ph}}^2}{D_L^2}, & \lambda > \lambda_{\text{CF}} \end{cases}
\]

(2)

\( T_{\text{ph}} \) is the temperature of the SN photosphere, \( R_{\text{ph}} \) is its radius, \( D_L \) is the luminosity distance of the SN, \( \lambda_{\text{CF}} \) is the cutoff wavelength, and \( \beta' \) is a dimensionless free parameter (Yan et al. 2020).

In general, the photosphere evolution can be described by Nicholl et al. (2017), which assumes that the expansion velocity of the early photosphere \( v_{\text{ph1}} \) of SNe is constant and the late-time temperature is a constant \( (T_\ell) \). We find, however, that the curve of the expansion velocity of the early photosphere can be divided into two episodes having different velocities \( v_{\text{ph1}} \) and \( v_{\text{ph2}} \), see the green dashed–dotted line and the red dashed line of Figure 1). The transition time when \( v_{\text{ph1}} \) becomes \( v_{\text{ph2}} \) is denoted as \( t_\tau \) and is relative to the time of the first photometry (see the orange vertical dotted line of Figure 1). The time interval between the explosion date and the time when \( v_{\phi1} \) becomes \( v_{\text{ph2}} \) (1) is \( t_\tau - t_{\text{shift}} \); here, \( t_{\text{shift}} \) is the explosion time relative to the first photometry. Therefore,
we generalize the photosphere modulus as follows:

$$R_{\text{ph}}(t) = \begin{cases} \nu_{\text{ph1}} t, & t \leq t_1 \text{ and } \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) > T_t \\ \nu_{\text{ph1}} + \nu_{\text{ph2}}(t - t_1), & t > t_1 \text{ and } \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) > T_t \\ \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/2})} \right)^{1/2}, & \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) \leq T_t \\ \nu_{\text{ph2}}(t - t_1) + \nu_{\text{pos}}(t - t_2), & t > t_1 \text{ and } \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) > T_t \end{cases}$$

(3)

$$T_{\text{ph}}(t) = \begin{cases} \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right)^{1/4}, & t \leq t_1 \text{ and } \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) > T_t \\ \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right)^{1/4}, & t > t_1 \text{ and } \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) > T_t \\ \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/2})} \right)^{1/4}, & \left( \frac{\log_{10}(t)}{\log_{10}(t_{1/4})} \right) \leq T_t \end{cases}$$

(4)

2.1. Modeling the Multiband LCs of SN 2018gk Using the $^{56}$Ni Model

We first fit the multiband LCs of SN 2018gk using the $^{56}$Ni model. Throughout this paper, $v_{\text{sc}}$ is assumed to be $v_{\text{ph1}}$. To include the energy deposited by $\gamma$-rays and positrons, we adopt the more complicated equation below (see, e.g., Valenti et al. 2008):

$$L_{\text{input}}(t)(1 - e^{-\tau_{\gamma}(t/\tau_{\gamma})}) = S^{\gamma}_{\text{Ni}}(\gamma) + S^{\gamma}_{\text{Co}}(\gamma) + S^{\gamma}_{\text{Co}}(\gamma) + S^{\gamma}_{\text{Co}}(\text{KE})$$

(5)

where $S^{\gamma}_{\text{Ni}}(\gamma) = \gamma_{\text{Ni}}M_{\text{Ni}}e^{-\tau_{\gamma}t}/\tau_{\gamma}(1 - e^{-\tau_{\gamma}t})$ is the source energy of the $^{56}$Ni decay, $M_{\text{Ni}}$ is the initial mass of $^{56}$Ni; $\gamma_{\text{Ni}} = 3.9 \times 10^{10}$ erg s$^{-1}$ g$^{-1}$ (Cappellaro et al. 1997; Sutherland & Wheeler 1984) is the energy generation rate of $^{56}$Ni. $\tau_{\gamma} = 8.8$ days is the lifetime of the $^{56}$Ni; $S^{\gamma}_{\text{Co}}(\gamma) = 0.81E_{\text{Co}}(1 - e^{-\tau_{\gamma}t/\tau_{\gamma}})$ is the source energy of the $^{56}$Co decay, the energy deposited by the $\gamma$-rays produced in the positron annihilation, and the source energy due to the kinetic energy of the positrons (Valenti et al. 2008), where

$$\frac{d\epsilon_{\text{Co}}}{dt} = \epsilon_{\text{Co}}M_{\text{Co}}e^{-\tau_{\gamma}t_{\text{sh}}}/\tau_{\gamma} - \epsilon_{\text{Co}}e^{-\tau_{\gamma}t/\tau_{\gamma}}$$

is the rate of energy production by the $^{56}$Co decay, $\epsilon_{\text{Co}} = 6.8 \times 10^{9}$ erg s$^{-1}$ g$^{-1}$ (Maeda et al. 2003) is the energy generation rate of $^{56}$Co, and $\tau_{\gamma} = 111.3$ days is the lifetime of $^{56}$Co.

By combining Equations (1), (2), (3), (4), and (5), we can construct the $^{56}$Ni model used to fit the multiband LCs of SN 2018gk. Considering the fact that the rise time is rather short, we fixed the value of $\kappa$ to be 0.05 cm$^2$ g$^{-1}$ throughout this paper to obtain a relatively large ejecta mass. The definitions, the units, and the priors of the parameters of the $^{56}$Ni model are listed in Table 1. We note that $\kappa_{\text{Ni}}$ and $\kappa_{\gamma}$ are also free parameters in our model.

The Markov Chain Monte Carlo (MCMC) method using the Python package emcee (Foreman-Mackey et al. 2013) is adopted to get the best-fitting parameters and their 1$\sigma$ range. We employ 20 walkers, each of which runs 30,000 steps for the $^{56}$Ni model. The 1$\sigma$ uncertainties correspond to the 16th and 84th percentiles of the posterior samples.

The fit of the $^{56}$Ni model is shown in Figure 2. The parameters and the corresponding corner plot are presented in Table 1 and Figure A1, respectively. The relevant parameters of the $^{56}$Ni model are $M_{\text{ej}} = 0.10 M_{\odot}$, $t_{\text{sh}} = 14.02$ days, $v_{\text{ph1}} = 1.52 \times 10^{9}$ cm s$^{-1}$, $v_{\text{ph2}} = 0.16 \times 10^{9}$ cm s$^{-1}$, $M_{\text{Ni}} = 1.59 M_{\odot}$, $T_t = 4921.90$ K, $t_{\text{sh}} = -1.76$ days (the offset of the best-fitting explosion epoch with respect to the explosion epoch

\begin{table}
\centering
\caption{Definitions, Units, Priors, Medians, 1$\sigma$ Bounds, and Best-fitting Values for the Parameters of the $^{56}$Ni Model}
\begin{tabular}{|c|c|c|c|c|}
\hline
Parameter & Definition & Unit & Prior & Best Fit \\
\hline
$M_{\text{ej}}$ & The ejecta mass & $M_{\odot}$ & [0.1, 50] & 0.10, 0.1 \pm 0.00 \, 0.10 \pm 0.00 \\
\hline
$t_w$ & The photospheric velocity transition time & day & [0, 1000] & 14.02, 14.03 \pm 0.00 \\
\hline
$v_{\text{ph1}}$ & The photospheric velocity of the first episode & km s$^{-1}$ & [0, 5] & 1.52, 1.52 \pm 0.01 \\
\hline
$v_{\text{ph2}}$ & The photospheric velocity of the second episode & km s$^{-1}$ & [0, 5] & 0.16, 0.16 \pm 0.01 \\
\hline
$M_{\text{Ni}}$ & The $^{56}$Ni mass & $M_{\odot}$ & [0.0, 4] & 1.59, 1.58 \pm 0.01 \\
\hline
log$\kappa_{\gamma}$ & The $\gamma$-ray opacity of $^{56}$Ni cascade decay & cm$^2$ g$^{-1}$ & [-1.568, 4] & -0.45, -0.44 \pm 0.01 \\
\hline
$\kappa_{\gamma}$ & The positron opacity & cm$^2$ g$^{-1}$ & [4, 14] & 4.00, 4.00 \pm 0.00 \\
\hline
$T_t$ & The temperature floor of the photosphere & K & [1000, 10$^4$] & 4921.90, 4928.23 \pm 130.50 \\
\hline
$t_{\text{sh}}$ & The explosion time relative to the first data & day & [-20, 0] & -1.76, -1.79 \pm 0.05 \\
\hline
$\lambda_{\text{CF}}$ & The cutoff wavelength & A & [0, 4000] & 2005.60, 2014.99 \pm 5.20 \\
\hline
$\beta^\text{0}$ & The dimensionless free parameter & & [0, 10] & 4.47, 3.61 \pm 2.40 \\
\hline
$\chi^2$/dof & & & & 9.30, 9.30 \\
\hline
\end{tabular}
\end{table}
adopted by B21 is 1.36 days), and \( \kappa_{\gamma,\text{Ni}} = 0.35 \text{ cm}^2 \text{ g}^{-1} \). Using these parameters, we find that the value of the \( \gamma \)-ray trapping parameter \( t_{0,\gamma,\text{Ni}} \) is 31.25 days. We find that the derived \( ^{56}\text{Ni} \) mass (1.59 \( M_\odot \)) is significantly larger than the derived ejecta mass (0.10 \( M_\odot \)).

It should be noted, however, that Arnett (1982)’s model we adopt above might overestimate the \( ^{56}\text{Ni} \) masses of SESNe (including Ib). We therefore calculate a more accurate value of the \( ^{56}\text{Ni} \) mass of SN 2018gk using the equation derived by Khatami & Kasen (2019):

\[
M_{\text{Ni}} = \frac{L_{\text{peak}} \beta^2 \gamma_{\text{peak}}^2}{2 \epsilon_{\text{Ni}} \tau_{\text{Ni}}^2} \left( \frac{1 - \epsilon_{\text{Co}}}{\epsilon_{\text{Ni}}} \right)
\times \left( 1 - (1 + \beta \gamma_{\text{peak}}/\tau_{\text{Ni}}) e^{-\beta \gamma_{\text{peak}}/\tau_{\text{Ni}}} \right)
\times \left( \frac{\epsilon_{\text{Co}}^2 \gamma_{\text{Co}}}{\epsilon_{\text{Ni}}^2 \tau_{\text{Co}}} \right)
\times \left( 1 - (1 + \beta \gamma_{\text{peak}}/\tau_{\text{Co}}) e^{-\beta \gamma_{\text{peak}}/\tau_{\text{Co}}} \right)^{-1}.
\]

The value of \( \beta \) is \( \sim 0.78 \) for SNe Ib (Afsariardchi et al. 2021).

Using the peak luminosity \( (L_{\text{peak}}) \) and the rise time \( (\gamma_{\text{peak}}) \) of the bolometric LC produced by the best-fitting parameters of the multiband LC fit, we find that the \( M_{\text{Ni}} \) value derived from Equation (6) is 0.90 \( M_\odot \). While this value is lower than the value derived by using Arnett (1982)’s model, it is significantly higher than the value of \( ^{56}\text{Ni} \) derived by B21 using the integral method of Katz et al. (2013) and is still larger than the mass of the ejecta. This indicates that the \( ^{56}\text{Ni} \) model cannot account for the LCs of SN 2018gk.

In Figure 3, we plot our synthesized bolometric LC of SN 2018gk, the power injection function curve derived from the parameters of B21 (\( M_{\text{Ni}} = 0.43 \ M_\odot, \ t_{0,\gamma,\text{Ni}} = 53 \) days), as well as the power injection function curve derived from our parameters (\( M_{\text{Ni}} = 1.59 \ M_\odot, \ t_{0,\gamma,\text{Ni}} = 31.25 \) days). For comparison, the curve derived from \( M_{\text{Ni}} = 1.85 \ M_\odot \) and an infinite \( t_{0,\gamma,\text{Ni}} \) is also plotted.

We find that the curves derived both from B21’s parameters and from our parameters can fit the late-time (\( > 75 \) days) synthesized bolometric LC, while the curve with infinite \( t_{0,\gamma,\text{Ni}} \) cannot fit the bolometric LC. It should be noted, however, that the curve using B21’s parameters is much lower than the bolometric luminosity of SN 2018gk around the peak, indicating that, in B21’s two-component diffusion model, the early-time LC is (mainly) powered by the internal energy.

In fact, the \( ^{56}\text{Ni} \) masses derived from the peak luminosity of SLSNe and luminous SNe are usually significantly higher than those derived from the tails (except for the cases in which the SLSNe are candidates for pair instability SNe), see, e.g., Table 3 of De Cia et al. (2018). The \( ^{56}\text{Ni} \) masses derived from tails are most reliable. Therefore, the peak luminosities of SLSNe and luminous SNe are usually assumed to be powered mainly by the energy sources (magnetar, interaction between ejecta and the circumstellar medium, fallback, or internal energy) rather than \( ^{56}\text{Ni} \) heating.

SN 2018gk is a luminous SN that has observational properties similar to those of SLSNe and luminous SNe. The large discrepancy between the inferred \( ^{56}\text{Ni} \) masses derived from the peak (see above) and from the tail (inferred by B21 using Katz et al. 2013) is also indicative of the necessity of introducing another energy source to account for the luminous peak.

2.2. Modeling the Multiband LCs of SN 2018gk Using the Magnetar plus \( ^{56}\text{Ni} \) Model

Although B21 show that the two-component diffusion model taking the internal energy and \( ^{56}\text{Ni} \) heating can fit the bolometric LC of SN 2018gk, the derived \( ^{56}\text{Ni} \) mass (\( \sim 0.43 \ M_\odot \)) is higher than the upper limit (\( \sim 0.2 \ M_\odot \)) of the \( ^{56}\text{Ni} \) mass that can be synthesized by the neutrino-power mechanism. To reduce the required \( ^{56}\text{Ni} \), B21 use the magnetar plus \( ^{56}\text{Ni} \) model to fit the bolometric LC of SN 2018gk. They find that the \( ^{56}\text{Ni} \) model only slightly reduces the \( ^{56}\text{Ni} \) mass to 0.3 \( M_\odot \), which is still larger than 0.2 \( M_\odot \). Moreover, they find that the derived parameters of the magnetars are very extreme: the initial period \( (P_0) \) and the magnetic field strength \( (B) \) of the magnetar are \( \sim 1.2 \) ms and \( \sim 4 \times 10^{15} \) G, respectively. These values are inconsistent with the typical values of the magnetars supposed to power the LCs of luminous SNe (see, e.g., Wang et al. 2015; Gomez et al. 2022) and SLSNe (see, e.g., Liu et al. 2017; Nicholl et al. 2017).

Hence, we check the magnetar plus \( ^{56}\text{Ni} \) model by fitting the LCs of SN 2018gk. The power function \( L_{\text{input}}(t) \) of the magnetar we adopt is

\[
L_{\text{input}}(t) = L_{\text{input,mag}}(t) = \frac{E_p}{\tau_p} \frac{1}{(1 + t/\tau_p)^2},
\]

where \( E_p \approx (1/2)I_{\text{mag}} \Omega_{\text{mag}}^2 \) is the rotational energy of a magnetar, \( \tau_p = 6I_{\text{mag}} c^3/B^2 R_{\text{mag}}^6 \Omega_{\text{mag}}^2 \) is the spin-down timescale of the magnetar (Kasen & Bildsten 2010), \( I_{\text{mag}} = (2/5)M_{\text{mag}} R_{\text{mag}}^2 \) is the moment of inertia of a magnetar, \( \Omega_{\text{mag}} = 2\pi/P_0 \) is the initial angular velocity \( (P_0 \) is the initial period of the magnetar), and \( B \) is the magnetic field strength of the magnetar. The mass \( (M_{\text{mag}}) \) and the radius \( (R_{\text{mag}}) \) of the magnetar are usually set to be \( 1.4 \ M_\odot \) and 10 km, respectively; using these two values, the canonical value of \( I_{\text{mag}} \) is \( \sim 10^{-5} \) g cm\(^2\) (see, e.g., Woosley 2010). The \( \gamma \)-ray opacity \( \kappa_\gamma \), in Equation (1) becomes \( \kappa_{\gamma,\text{mag}} \).

By combining Equations (1), (2), (3), (4), (5), and (7), the magnetar plus \( ^{56}\text{Ni} \) model can be constructed. The definitions, the units, and the priors of the parameters of the magnetar plus \( ^{56}\text{Ni} \) model are listed in Table 2. The MCMC method using the Python package emcee is adopted to get the best-fitting parameters and their 1\( \sigma \) range. We employ 20 walkers, each of

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Figure 2. The best fits (the solid curves) of the multiband LCs of SN 2018gk using the \( ^{56}\text{Ni} \) model. The shaded regions indicate 1\( \sigma \) bounds of the parameters. The data are from Table 1 of B21; triangles represent upper limits.
which runs 30,000 steps for the magnetar plus $^{56}$Ni model. The 1σ uncertainties correspond to the 16th and 84th percentiles of the posterior samples.

The fit of the magnetar plus $^{56}$Ni model is shown in Figure 4. The parameters and the corresponding corner plot are presented in Table 2 and Figure A2, respectively. The relevant parameters of the magnetar plus $^{56}$Ni model are $M_{\text{ej}} = 1.65 M_{\odot}$, $P_0 = 10.42$ ms, $B = 6.52 \times 10^{14}$ G, $M_{56} = 0.08 M_{\odot}$, $t_{\text{fit}} = 17.15$ days, $v_{\text{ph1}} = 1.07 \times 10^3$ cm s$^{-1}$, $v_{\text{ph2}} = 0.11 \times 10^3$ cm s$^{-1}$, $T_1 = 5254.04$ K, $t_{\text{shift}} = -6.35$ days (the offset of the best-fitting explosion epoch with respect to the explosion epoch adopted by B21 is 5.95 days), $\kappa_{56,\text{mag}} = 0.19$ cm$^2$ g$^{-1}$ ($t_{0,56,\text{Ni}} = 132.17$ days), and $\kappa_{56,\text{mag}} = 0.028$ cm$^2$ g$^{-1}$ ($t_{0,56,\text{Ni}} = 50.83$ days).

We find that, using the same scenario (the magnetar plus $^{56}$Ni), our derived $P_0$ (10.42 ms) is significantly longer than that (1.2 ms) of B21; our derived $B$ ($6.52 \times 10^{14}$ G) is about 1/6 of that ($4 \times 10^{15}$ G) of B21. We suggest that the discrepancies between our values of $B$ and $P_0$ and those of B21 might be due to the differences in explosion epoch and other parameters, since the large parameter space involved in the magnetar plus $^{56}$Ni model might yield another parameter set that can fit the same LCs. However, our derived values of $B$ and $P_0$ are not extreme and are comparable to those of luminous SNe studied in the literature, indicating that the magnetar plus $^{56}$Ni model is reasonable.

Furthermore, our derived $^{56}$Ni mass is 0.08 $M_{\odot}$, which can be reduced to 0.05 $M_{\odot}$ by using Equation (6). This value is much lower than the $^{56}$Ni mass derived by using the $^{56}$Ni model, suggesting that the magnetar can effectively reduce the $^{56}$Ni needed to power the LCs of SN 2018gk. More importantly, the derived $^{56}$Ni is lower than the upper limit ($\sim 0.2 M_{\odot}$) of the $^{56}$Ni mass that can be synthesized by the

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**Table 2**

| Parameters | Definition | Unit | Prior | Best Fit | Median |
|------------|------------|------|-------|----------|--------|
| $M_{\text{ej}}$ | The ejecta mass | $M_\odot$ | [0.1, 50] | 1.65 | 1.61$^{+0.08}_{-0.06}$ |
| $P_0$ | The initial period of the magnetar | ms | [0.8, 50] | 10.42 | 10.43$^{+0.03}_{-0.03}$ |
| $B$ | The magnetic field strength of the magnetar | $10^{14}$ G | [0.1, 100] | 6.52 | 6.48$^{+0.11}_{-0.11}$ |
| $t_{\text{ph}}$ | The photospheric velocity transition time | day | [0, 100] | 17.15 | 17.01$^{+0.11}_{-0.11}$ |
| $v_{\text{ph1}}$ | The photospheric velocity of the first episode | $10^3$ cm s$^{-1}$ | [0, 5] | 1.07 | 1.07$^{+0.01}_{-0.01}$ |
| $v_{\text{ph2}}$ | The photospheric velocity of the second episode | $10^3$ cm s$^{-1}$ | [0, 5] | 0.11 | 0.11$^{+0.01}_{-0.01}$ |
| $M_{56}$ | The $^{56}$Ni mass | $M_\odot$ | [0, 0.2$M_\odot$] | 0.08 | 0.08$^{+0.06}_{-0.06}$ |
| $\log v_{\gamma,\text{mag}}$ | The $\gamma$-ray opacity of magnetar photons | cm$^2$ g$^{-1}$ | [-2, 4] | -1.55 | -1.55$^{+0.02}_{-0.02}$ |
| $\log v_{\gamma,\text{Ni}}$ | The $\gamma$-ray opacity of $^{56}$Ni-cascade-decay photons | cm$^2$ g$^{-1}$ | [-1.568, 4] | -0.72 | -0.72$^{+0.04}_{-0.04}$ |
| $\kappa_\gamma$ | The positron opacity | cm$^2$ g$^{-1}$ | [4, 14] | 7.02 | 8.95$^{+3.35}_{-3.35}$ |
| $T_1$ | The temperature floor of the photosphere | K | [1000, 10$^4$] | 5254.04 | 5244.27$^{+12.10}_{-11.11}$ |
| $t_{\text{shift}}$ | The explosion time relative to the first data | day | [-20, 0] | -6.35 | -6.29$^{+0.07}_{-0.06}$ |
| $\lambda_{\text{CF}}$ | The cutoff wavelength | Å | [0, 4000] | 2007.99 | 2019.53$^{+1302.88}_{-13.33}$ |
| $\beta^0$ | The dimensionless free parameter | | [0, 10] | 3.82 | 1.95$^{+0.33}_{-0.33}$ |
| $\chi^2$/dof | | | | 6.08 | 6.08 |

**Note.** The values of $\chi^2$/dof (reduced $\chi^2$, dof = degree of freedom) are also presented.
neutrino-power mechanism, and is comparable to the $^{56}$Ni masses of typical SNe IIb.\textsuperscript{7}

2.3. Modeling the Multiband LCs of SN 2018gk Using the Fallback plus $^{56}$Ni Model

The fallback and fallback plus $^{56}$Ni models are also used to fit the multiband LCs of some SNe (see, e.g., the references of B21 and Moriya et al. 2018). B21 disfavor the fallback model since the $^{56}$Ni synthesized by the SN shock is accreted onto the central compact remnant and very low or no $^{56}$Ni mass can survive. Here, we check the possibility that the multiband LCs of SN 2018gk can be fitted by the fallback plus $^{56}$Ni model.

The power function $L_{\text{input}}(t)$ of the fallback model is (Moriya et al. 2018)

$$L_{\text{input}}(t) = L_{\text{input,fb}}(t) = \begin{cases} L_1(t_{\text{fb}}/1 \text{ s})^{-5/3}, & t < t_{\text{fb}} \\ L_1(t/1 \text{ s})^{-5/3}, & t \geq t_{\text{fb}} \end{cases}$$

(8)

where $L_1$ is a constant and $t_{\text{fb}}$ is the transition time when the constant becomes a power-law function (Moriya et al. 2018).

By combining Equations (1), (2), (3), (4), (5), and (8), the fallback plus $^{56}$Ni model can be constructed. The definitions, the units, and the priors of the parameters of the fallback plus $^{56}$Ni model are listed in Table 3. The MCMC method using the Python package emcee is adopted to get the best-fitting parameters and their 1$\sigma$ range. We employ 20 walkers, each of which runs 30,000 steps for the fallback plus $^{56}$Ni model. The 1$\sigma$ uncertainties correspond to the 16th and 84th percentiles of the posterior samples.

The fit of the fallback plus $^{56}$Ni model is shown in Figure 5. The parameters and the corresponding corner plot are presented in Table 3 and Figure A3, respectively. We find that the LCs can be well fitted by the fallback plus $^{56}$Ni model, although the LCs are rather narrow. The relevant parameters of the fallback plus $^{56}$Ni model are $M_{ej} = 1.70 M_\odot$, $L_1 = 8.71 \times 10^{53}$ erg s$^{-1}$, $t_{\text{fb}} = 14.12$ days, $M_{Ni} = 0.05 M_\odot$, $t_{\text{shift}} = 19.32$ days, $\varphi_{\text{fb}} = 0.91 \times 10^8$ cm s$^{-1}$, $\varphi_{\text{Ni}} = 0.13 \times 10^8$ cm s$^{-1}$, $T_1 = 5235.48$ K, $t_{\text{shift}} = -8.11$ days (the offset of the best-fitting explosion epoch with respect to the explosion epoch adopted by B21 is 7.71 days), $\kappa_{\gamma,\text{fb}} = 0.20 \text{ cm}^2 \text{g}^{-1}$ ($t_{\text{shift}} = 145.53$ days), and $\kappa_{\gamma,\text{Ni}} = 0.031 \text{ cm}^2 \text{g}^{-1}$ ($t_{\text{shift}} = 58.60$ days). Using Equation (6), $^{56}$Ni mass is reduced to 0.03 $M_\odot$.

Based on the derived parameters, we can infer the accretion mass $M_{\text{acc}}$, which can be expressed as (Moriya et al. 2018)

$$\eta M_{\text{acc}} c^2 = \int_0^{\infty} L_{\text{input,fb}}(t) dt = 2.5L_1 t_{\text{fb}}^{-2/3}$$

(9)

where $\eta$ is the efficiency of converting accretion to input energy. The typical value of $\eta$ is assumed to be $\sim 0.001$ (Dexter & Kasen 2013). However, $\eta$ can also be supposed to be an

![Figure 5](image-url)
extreme value of ∼0.1 (e.g., McKinney 2005; Kumar et al. 2008; Gilkis et al. 2016). Therefore, the range of η can be ∼0.001−0.1. According to the derived values of $L_\text{tr}$ and $f_\text{tr,fb}$, we find that the accreted mass of SN 2018gk is 0.001−0.11 $M_\odot$.

The problem of the fallback plus $^{56}$Ni model is that a decreasing $^{56}$Ni mass needs an input function including a time-varying $^{56}$Ni mass. However, this effect can be neglected if $M_{\text{acc}}$ is very small (e.g., less than 0.01 $M_\odot$). The accretion mass $M_{\text{acc}}$ is only 0.001−0.011 $M_\odot$ if η is 0.01−0.1; the accretion mass can reach about 0.1 $M_\odot$, which is larger than the initial $^{56}$Ni mass ($0.03$ $M_\odot$) we derived, if η is as low as about 0.001. Therefore, the fallback plus $^{56}$Ni model favors a relatively large $M_{\text{acc}}$, and hence a large accreted $^{56}$Ni mass, greater than the $^{56}$Ni mass derived by the model. Therefore, although the fallback plus $^{56}$Ni model cannot be excluded, its validity depends on the value of η.

### 3. The NIR Excesses of SN 2018gk and the Properties of Possible Dust

As pointed out by B21, SN 2018gk shows NIR excesses in the $H$-band flux, which can be due to the strong emission in the $H$ band or the dust emission. Our multiband fits also show the $H$-band excesses at the late epochs. Furthermore, our blackbody fits for the optical—NIR SEDs at five epochs when at least $J$- and $H$-band photometry are available demonstrate that, while the SEDs at the first two epochs do not show NIR excesses, those at the other three epochs do show evident NIR excesses (see Figure 6; the derived parameters are listed in Table 4).

We suppose that the NIR excesses of the SEDs are due to dust emission, and adopt a blackbody plus dust emission model to fit the optical—NIR SEDs of SN 2018gk. The details of the model can be found in Gan et al. (2021), and we suppose that the dust size distribution follows a power-law function (see, e.g., Cao et al. 2022 and the references therein). The MCMC method is also used. The free parameters of the model are the dust mass $M_\text{d}$, the dust temperature $T_\text{d}$, and the temperature of the SN photosphere $T_{\text{ph}}$, and its radius $R_{\text{ph}}$. We suppose that the dust might be graphite or silicate. The fits of the model are shown in Figure 7; the derived parameters are listed in Table 5.

We find that the putative dust mass is ∼(2.9−19.4) × 10$^{-3}$ $M_\odot$ or ∼(3.5−24.9) × 10$^{-5}$ $M_\odot$ for graphitic or silicate dust, and the temperature of the dust is ∼730−850 K or ∼780−880 K for the two cases. The derived median values of the dust mass are in the range from a few 10$^{-3}$ to a few 10$^{-2}$ $M_\odot$ of those of the dust of many SNe (see, e.g., Table 5 of Fox et al. 2013). Moreover, the derived temperature are lower than the evaporation temperatures of silicate (∼1100−1500 K, Laor & Draine 1993; Mattila et al. 2008; Gall et al. 2014) and graphite (∼1900 K, Stritzinger et al. 2012). These two facts support the assumption that the NIR excesses are from the dust emission.

However, the absence of data in the $K$ band and other bands with longer effective wavelengths at the three epochs prevents us from placing more stringent constraints on the temperature and mass of the putative dust. In particular, the absence of data in bands with longer effective wavelengths would result in a longer derived peak wavelength of the SEDs of the dust.
emission. A temperature lower than the real value is therefore favorable. Hence, the dust temperature of SN 2018gk we derive can be regarded as a lower limit to the real temperature of the putative dust.

4. Discussion

4.1. The Mass of the Ejecta

The ejecta mass of SN 2018gk derived from the magnetar plus $^{56}$Ni model we adopt is $\sim 1.65 \, M_\odot$. According to the analysis of B21, $M_{ZAMS}$ and the helium core mass just prior to the explosion are $\sim 20–25 \, M_\odot$ and $\sim 6–8 \, M_\odot$. After removing the putative magnetar with mass of $1.4 \, M_\odot$, the ejecta mass is $\sim 4.6–6.6 \, M_\odot$, which is larger than our derived ejecta mass. It seems that the discrepancy between the two values disfavors both models.

The contradiction can be eliminated since (1) the magnetar mass can be up to $\sim 2.0–2.5 \, M_\odot$, and then the lower limit of the ejecta can be reduced to $3.5 \, M_\odot$; (2) the final masses of the progenitors of SESNe are sensitive to metallicity and $M_{ZAMS}$, so an SESN progenitor with $M_{ZAMS} \sim 18–25 \, M_\odot$ might yield an ejecta mass of $2.39–3.61 \, M_\odot$ (Dessart et al. 2011); (3) the analysis of B21 is based on the model of single-star evolution, while binary-star evolution can reduce the helium core masses of the progenitors of SESNe (Yoon et al. 2010); (4) a smaller $\kappa$ would result in a larger ejecta mass.

Hence, we suggest that the ejecta mass of SN 2018gk derived from the magnetar plus $^{56}$Ni model and the model itself are reasonable. The discrepancy between the two values might indicate that the progenitor of SN 2018gk was in a binary system and/or had a low metallicity, or the explosion of SN 2018gk left a massive magnetar.

4.2. The Theoretical Bolometric Light Curve and the Evolution of Temperature and Radius of SN 2018gk

Based on the best-fitting parameters of the magnetar plus $^{56}$Ni model obtained from the multiband LCs, the theoretical bolometric LC and the evolution of temperature and radius can be reproduced; see Figure 8. For comparison, the same three curves reproduced by the best-fitting parameters of the model.
adopting the photosphere modulus of Nicholl et al. (2017) are also plotted in the same figure. We find that while the theoretical bolometric LC of both models can fit the bolometric LC derived from the photometry, the curves of temperature and radius evolution reproduced by our model that use a generalized photosphere modulus can better match those derived from the photometry. This indicates that the photosphere velocity has decreased before the temperature reaches its floor ($T_f$), and demonstrates the necessity of generalizing the photosphere modulus.

We find the rise time of the bolometric LC of SN 2018gk reproduced by the best-fitting parameters of the magnetar plus $^{56}$Ni model is $\sim$13.2 days, which is significantly longer than the rise time ($\lesssim$5 days, see Figure 14 of B21) of the bolometric LC reproduced by B21 using the magnetar plus $^{56}$Ni model. The peak luminosity of the bolometric LC reproduced is $\sim$4.35 x $10^{43}$ erg s$^{-1}$, which is half of the peak luminosity ($\sim$10$^{44}$ erg s$^{-1}$) derived by B21 using the magnetar plus $^{56}$Ni model. Our derived peak luminosity of the bolometric LC of SN 2018gk also suggests that SN 2018gk is one of the luminous SNe that bridge the gap between SLSNe (whose peak bolometric luminosities are $\gtrsim$7 x $10^{43}$ erg s$^{-1}$, Gal-Yam 2012) and normal-luminosity SNe.

5. Conclusions

SN 2018gk is a luminous SN I Ib whose peak luminosity is between those of SLSNe and normal SNe. In this paper, we perform a comprehensive study of the physical properties of SN 2018gk. Based on the SED fits, we find that the early-time photospheric velocity varies from a larger value to a smaller one before the photosphere reaches its floor ($T_f$), and demonstrates the necessity of generalizing the photosphere modulus.

We find the rise time of the bolometric LC of SN 2018gk reproduced by the best-fitting parameters of the magnetar plus $^{56}$Ni model is $\sim$13.2 days, which is significantly longer than the rise time ($\lesssim$5 days, see Figure 14 of B21) of the bolometric LC reproduced by B21 using the magnetar plus $^{56}$Ni model. The peak luminosity of the bolometric LC reproduced is $\sim$4.35 x $10^{43}$ erg s$^{-1}$, which is half of the peak luminosity ($\sim$10$^{44}$ erg s$^{-1}$) derived by B21 using the magnetar plus $^{56}$Ni model. Our derived peak luminosity of the bolometric LC of SN 2018gk also suggests that SN 2018gk is one of the luminous SNe that bridge the gap between SLSNe (whose peak bolometric luminosities are $\gtrsim$7 x $10^{43}$ erg s$^{-1}$, Gal-Yam 2012) and normal-luminosity SNe.
The $^{56}\text{Ni}$ model, though the fallback plus $^{56}\text{Ni}$ model cannot be excluded.

The $^{56}\text{Ni}$ mass (0.05 $M_\odot$) derived here by using the magnetar plus $^{56}\text{Ni}$ model is significantly lower than that ($\sim0.9 M_\odot$) required by the $^{56}\text{Ni}$ model adopted here, indicating that the magnetar can significantly reduce the $^{56}\text{Ni}$ mass required to power the LCs of SN 2018gk. The derived $^{56}\text{Ni}$ mass of the magnetar plus $^{56}\text{Ni}$ model is about 1/6 of the value ($\sim0.3 M_\odot$) derived by B21 using the same scenario, and comparable to the $^{56}\text{Ni}$ masses of typical SNe Iib. Moreover, our derived $^{56}\text{Ni}$ mass is lower than the upper limit ($0.2 M_\odot$) of the $^{56}\text{Ni}$ mass that can be synthesized by neutrino-powered CCSNe.

The value of $P_0$ (10.42 ms) derived from the magnetar plus $^{56}\text{Ni}$ model we adopt is about eight times that (1.2 ms) derived by B21; the derived value of $B$ ($6.52 \times 10^{14}$ G) is about 1/6 of that ($4 \times 10^{15}$ G) derived by B21. A larger $P_0$ usually results in a lower input power and a lower peak luminosity. In general, magnetars with $P_0 \sim 1-5$ ms and $B \sim 10^{14-10^{15}}$ G would power SLSNe (see, e.g., Liu et al. 2017; Nicholl et al. 2017), while magnetars with $P_0 \sim 5-20$ ms and $B \sim 10^{13-10^{15}}$ G would power luminous SNe (see, e.g., Wang et al. 2015; Gomez et al. 2022) with rare exceptions. Hence, we suggest that our derived parameters of the magnetar supposed to power the LCs of SN 2018gk are reasonable, since SN 2018gk is a luminous SN rather than an SLSN.

Therefore, we suggest that the magnetar plus a moderate amount of $^{56}\text{Ni}$ can be responsible for the luminous LCs of SN 2018gk. To our knowledge, other luminous SNe Iib requiring central engines (plus $^{56}\text{Ni}$) to account for their LCs are PTF10hgi and DES14X2fna. So SN 2018gk might be a rare SNe Iib mainly powered by a central engine.

Based on the best-fitting parameters of the magnetar plus $^{56}\text{Ni}$ model, we plot the bolometric LC and the evolution of the photospheric temperature and photospheric radius of SN 2018gk, and compare them with those from the SED fits. The peak of the theoretical bolometric LC of SN 2018gk is $\sim4.35 \times 10^{43}$ erg s$^{-1}$, which is below the fiducial threshold of SLSNe ($\lesssim 7 \times 10^{44}$ erg s$^{-1}$; Gal-Yam 2012) and the peak luminosity ($\sim10^{44}$ erg s$^{-1}$) derived by B21. The rise time of the theoretical bolometric LC of SN 2018gk is $\sim13.2$ days, which is comparable to those of many SESNe.

Moreover, we find that the theoretical evolution of the temperature and the radius of the photosphere is well matched by that from SED fits. For comparison, we also plot the theoretical evolution of the temperature and the radius of the photosphere based on the simple photosphere modulus that assumes the photosphere velocity is constant before the temperature floor is reached; this deviates from those from the SED fits from 30 to 60 days after the derived explosion date. We suggest that the conventional photosphere modulus cannot describe the early-time photospheric evolution of a fraction of SNe and a generalized photosphere modulus should be considered as an alternative.

Finally, we find that the blackbody plus dust emission model can account for the NIR excesses of the SEDs of SN 2018gk at some epochs. The derived masses of the dust are $\sim(2.9-19.4) \times 10^{-3} M_\odot$ ($\sim(3.5-24.9) \times 10^{-3} M_\odot$) for graphite (silicate) grains; the derived temperatures of the dust of the SN are $\sim730$–$850$ K ($\sim780$–$880$ K) for graphite (silicate) grains. Due to the absence of photometry in the K band and other bands with longer effective wavelengths, the real parameters cannot be well constrained, and the derived dust temperature might be a lower limit to the real temperature of the dust.

We thank the anonymous referee for helpful comments and suggestions that have allowed us to improve this manuscript. Wang Tao thanks Li Jia-Wei (李佳伟), Wang Shuai-Cong (王帅聪), Shi Deng-Wang (石登旺), Bai Song-Yao (白松瑶), and Li Jing-Yao (李京瑶) for helpful discussion. This work is supported by National Natural Science Foundation of China (grant Nos. 11963001, 12133003, 11833003, 11973020 (C0035736), and U1938201).

**Appendix**

Figures A1, A2, and A3 present the corner plots of the $^{56}\text{Ni}$ model, the magnetar plus $^{56}\text{Ni}$ model, and the fallback plus $^{56}\text{Ni}$ model, respectively.
Figure A1. The corner plot of the $^{56}$Ni model. The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the $1\sigma$ bounds of the parameters.
Figure A2. The corner plot of the magnetar plus $^{56}\text{Ni}$ model. The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the $1\sigma$ bounds of the parameters.
Figure A3. The corner plot of the fallback plus $^{56}$Ni model. The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the 1σ bounds of the parameters.

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