ChinaRxiv

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202410.00052

The Energy Sources and the Explosion Mechanism of Ca-rich Supernova PTF 10iuv (Postprint)

Authors: Qiu-Ping Huang, Shan-Qin Wang, Tao Wang, Wen-Pei Gan, Deng-Wang Shi, Liu-Yi Wang, and En-Wei Liang

Date: 2024-10-08T00:00:00+00:00

Abstract

In this paper, we perform the detailed modeling for the light curves (LCs) of PTF 10iuv which is a calcium-rich (Ca-rich) supernova (SN) to constrain the physical properties of its ejecta and the energy sources, as well as the explosion mechanism. We find that the 56Ni model and the 56Ni plus circumstellar interaction model fail to explain the LCs, while the four-element (56Ni, 48Cr, 52Fe, and 44Ti) model can account for the LCs. The ejecta mass of PTF 10iuv derived by the model (1.52−0.25+0.34M) is consistent with that of the merger of a sub-Chandrasekhar mass white dwarf. The early-time LCs were mainly powered by 56Ni whose mass is 0.03 M , while the contributions of 48Cr and 52Fe can be neglected. The derived 44Ti mass (0.25 M) is 1.8 times the upper limit of the derived 44Ti mass of Ca-rich SN 2005E. We suggest that subtracting the contributions of the host-galaxy, which are unknown, and including the flux from other long-lived elements (e.g., 57Co, 55Fe, 60Co) can reduce the amount of 44Ti, and that this value can be regarded as an upper limit.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:095009 (13pp), 2024 September
© 2024. National Astronomical Observatories, CAS and IOP Publishing Ltd. Printed in China and the U.K.
https://doi.org/10.1088/1674-4527/ad6bd5

The Energy Sources and the Explosion Mechanism of Ca-rich Supernova PTF 10iuv

Qiu-Ping Huang (黄秋萍)[1], Shan-Qin Wang (王善钦)[1], Tao Wang (王涛)[2], Wen-Pei Gan (甘文沛)[3], Deng-Wang Shi (石登旺)[1], Liu-Yi Wang (王浏毅)[1], and En-Wei

ChinaRxiv 中X

Liang (梁恩维)[1]

[1] Guangxi Key Laboratory for Relativistic Astrophysics, School of Physical Science and Technology, Guangxi University, Nanning 530004, China; shanqin-wang@gxu.edu.cn
[3] Nanjing Hopes Technology Co., Ltd., Nanjing 210000, China

Received 2024 May 9; revised 2024 July 22; accepted 2024 July 24; published 2024 September 16

Abstract

In this paper, we perform detailed modeling of the light curves (LCs) of PTF 10iuv, a calcium-rich (Ca-rich) supernova (SN), to constrain the physical properties of its ejecta, the energy sources, and the explosion mechanism. We find that the 56Ni model and the 56Ni plus circumstellar interaction model fail to explain the LCs, while a four-element (56Ni, 48Cr, 52Fe, and 44Ti) model can successfully account for them. The ejecta mass of PTF 10iuv derived from the model (1.52 ± 0.25 M) is consistent with that expected from the merger of a sub-Chandrasekhar mass white dwarf. The early-time LCs were mainly powered by 56Ni with a mass of 0.03 M , while the contributions of 48Cr and 52Fe can be neglected. The derived 44Ti mass (0.25 M) is 1.8 times the upper limit of the 44Ti mass derived for Ca-rich SN 2005E. We suggest that subtracting the unknown contributions from the host galaxy and including flux from other long-lived elements (e.g., 57Co, 55Fe, 60Co) can reduce the required amount of 44Ti, and that this value should be regarded as an upper limit.

Key words: (stars:) supernovae: general – (stars:) supernovae: individual (PTF 10iuv) – (stars:) novae – cataclysmic variables

1. Introduction

Supernovae (SNe) are explosions of white dwarfs (WDs) in binary systems or aged massive stars. According to their spectra at photospheric phases, most SNe can be divided into types: Ia, Ib, Ic, IIb, and II (Filippenko 1997; a more detailed classification scheme can be found in Gal-Yam 2017). It is widely believed that type Ia SNe result from the explosions of WDs, while most other sub-types originate from the explosions of massive stars.

Over the past two decades, several dozen new optical transients classified as calcium-rich (Ca-rich) SNe or transients have been confirmed (e.g., Filippenko et al. 2003; Kawabata et al. 2010; Perets et al. 2010; Sullivan et al. 2011; Kasliwal et al. 2012; Valenti et al. 2014; Lunnan et al. 2017; De et al. 2018, 2020; Lee et al. 2019; Jacobson-Galán et al. 2020b). Although the spectra of most confirmed Ca-rich SNe at photospheric phases can also be classified as types Ia (SN 2016hnk, SN 2019ofm; Jacobson-Galán et al. 2020a; De et al. 2020), Ib (e.g., SN 2005E, SN 2005cz, SN 2007ke, PTF 10iuv, PTF 11kmb; Puckett & Dowdle 2000; Aazami & Li 2001; Filippenko et al. 2003; Puckett et al. 2003;

Pugh & Li 2003; Dimai et al. 2005; Graham et al. 2005; Chu et al. 2007; Perets et al. 2010; Kasliwal et al. 2012; Foley 2015; Lunnan et al. 2017; De et al. 2018, 2020; Jacobson-Galán et al. 2020a, 2020b; Ertini et al. 2023), Ic (SN 2012hn, SN 2018gwo, SN 2022oqm; Valenti et al. 2014; De et al. 2020; Irani et al. 2024), and IIb (iPTF15eqv, SN 2018jak, SN 2019ehk, SN 2020sbw, SN 2021M, SN 2021pb, SN 2021sjt; Cao et al. 2015; De et al. 2021; Das et al. 2023), their late-phase nebular spectra show prominent calcium (Ca) and weak oxygen (O) lines, which are distinct from those of normal SNe Ia, Ib, Ic, and IIb (see Taubenberger 2017). Additionally, there are several Ca-rich SNe whose spectral types are unknown (PTF 09dav, PTF 11bij, PTF 12bho, SN 2019bkc, SN 2019pof; Sullivan et al. 2011; Chen et al. 2020; Prentice et al. 2020).

The explosion sites of Ca-rich SNe also differ from those of normal SNe Ib and Ic. In contrast to SNe Ib and Ic, which are found in star-forming regions, almost all Ca-rich SNe occur in old environments far from the center of their (potential) host galaxies (see Taubenberger 2017 and references therein). Furthermore, most Ca-rich SNe have fast-evolving light curves (LCs), indicating that their ejecta masses (M) are rather small, comparable to those of some ultra-stripped-envelope SNe Ic (e.g., SN 2005ek; Drout et al. 2013). Perets et al. (2010) found that the ejecta mass of SN 2005E is 0.3 ± 0.1 M and suggested that the ejecta originated from the ejected helium shell surrounding a WD. To our knowledge, all confirmed Ca-rich SNe are low-luminosity cases with peak absolute magnitudes between −14 and −17.5 mag. Assuming that the LCs of Ca-rich SNe are powered by the cascade decay of radioactive elements, these low peak luminosities imply that the total masses of synthesized radioactive elements are significantly lower than those produced by normal SNe Ib and Ic.

The features of Ca-rich SNe challenge standard SN explosion scenarios. For instance, while the progenitors of normal SNe Ib and Ic are believed to be massive stars, the progenitors of Ca-rich SNe Ib are suggested to be WDs in binary systems (Perets et al. 2010; Lyman et al. 2014; Foley 2015; Lunnan et al. 2017; Zenati et al. 2023). Furthermore, numerical simulations (Bildsten et al. 2007; Shen & Bildsten 2009; Shen et al. 2010; Waldman et al. 2011; Woosley & Kasen 2011) suggest that explosions of sub-Chandrasekhar mass WDs can reproduce some features (low peak luminosities, low ejecta masses, high abundance of Ca, etc.) of Ca-rich SNe Ib.

Although the explosion mechanisms and progenitor systems of Ca-rich SNe remain elusive, it is possible to constrain their physical parameters and infer their energy sources. Some groups (e.g., Kasliwal et al. 2012; De et al. 2018, 2020) have used the 56Ni cascade decay (56Ni → 56Co → 56Fe) model to estimate M , 56Ni masses (M_{Ni}), and other explosion parameters. However, the assumption that the LCs of Ca-rich SNe were solely powered by 56Ni cascade decay is not always valid. Studies of the nucleosynthesis of SN 2005E (Perets et al. 2010) and explosions of sub-Chandrasekhar mass WDs (Bildsten et al. 2007; Shen & Bildsten 2009; Shen et al. 2010; Waldman et al. 2011; Woosley & Kasen 2011) show that other short-lived radioactive elements (e.g., 52Fe, 48Cr) and long-lived radioactive elements (e.g., 44Ti) should also be produced by Ca-rich SNe. Jacobson-Galán et al. (2021) used a radioactive model including contributions from 56Co and 57Co (from the decay of 56Ni and 57Ni) to fit the late-time bolometric LC of Ca-rich SN 2019ehk, obtaining the 56Co mass and constraining the upper limit of the 57Co mass. In several numerical models, the 56Ni masses can be as low as 10^{-7}–10^{-4} M , which are significantly lower than the 48Cr masses in the same models (Waldman et al. 2011). In these models, the contribution from the cascade decay of 48Cr (48Cr → 48V → 48Ti) is significantly larger than that of 56Ni at early epochs (see, e.g., Figure 4 [Figure 4: see original paper] of Waldman et al. 2011). Additionally, the amount of 44Ti synthesized in explosions of sub-Chandrasekhar mass WDs can be up to 10^{-1} M (Perets et al. 2010; Waldman et al. 2011; Zenati et al. 2023), 3–4 orders of magnitude larger than the mass of 44Ti (M_{Ti}) from core-collapse SNe (CCSNe, 1–15 × 10^{-5} M ; The et al. 2006) and SNe Ia (0.87–2.7 × 10^{-5} M ; Timmes et al. 1996). Although the contribution from the cascade decay of 44Ti (44Ti → 44Sc → 44Ca) can be neglected in early-time LCs of SNe, it can change the shapes of the LCs of some Ca-rich SNe as early as 100 days and dominate the late-time LCs (see, e.g., Figure 4 of Waldman et al. 2011).

In this paper, we perform a theoretical study of PTF 10iuv (=SN 2010et) (Kasliwal et al. 2012), one of the Ca-rich SNe observed over 200–300 days. PTF 10iuv was detected by the Palomar Transient Factory (PTF) at a redshift (z) of 0.023 on 2010 May 31, when its r-band magnitude was 21.2 (see Kasliwal et al. 2012; Dessart & Hillier 2015; Moriya et al. 2017 and references therein). Follow-up photometric observations of PTF 10iuv were performed using Bgriz filters of the Palomar 60-inch telescope (P60), the Large Format Camera (LFC) on the Palomar 200-inch telescope (P200), and the Low Resolution Imaging Spectrometer (LRIS) on the Keck I telescope. The r-band LC peaked at 19.0 mag in 10 days and declined rapidly (1 magnitude within 12 days) (Kasliwal et al. 2012). One month later, PTF 10iuv evolved slowly at a rate of 0.02 mag day^{-1} for three months, followed by a decline rate of 0.005 mag day^{-1}.

The spectra of PTF 10iuv indicate that it is a Ca-rich SN Ib. The distance of PTF 10iuv from the nearest galaxy that might be its host galaxy is 37 kpc (Kasliwal et al. 2012). Kasliwal et al. (2012) used the input power function of the 56Ni cascaded decay to fit the r-band LC of PTF 10iuv, finding that the flux of late-time data is brighter than that reproduced by 56Ni cascaded decay. They suggested that the late-time excesses relative to the 56Ni input luminosity might be due to host-galaxy contamination or contributions from other radioactive elements, e.g., 44Ti. However, as pointed out by Kasliwal et al. (2012), the 44Ti mass required would be 2 M if the late-time flux were powered solely by 44Ti decay.

Kasliwal et al. (2012) suggested that modeling the LCs of PTF 10iuv could better constrain models including contributions from 48Cr, 44Ti, and 52Fe, since photometry in both the rising and late phases is available. However, detailed modeling has not been performed. This is the aim of our study.

In Section 2, we use the 56Ni model and other, more complicated models to fit the multi-band LCs of PTF 10iuv. In Section 3, we discuss the physical parameters and possible implications. In Section 4, we draw conclusions. Throughout this paper, we assume Ω_m = 0.315, Ω_Λ = 0.685, H_0 = 67.3 km s^{-1} Mpc^{-1} (Planck Collaboration et al. 2014). The values of foreground Galactic reddening are from Schlafly & Finkbeiner (2011).

2. Modeling the Multi-band LCs of PTF 10iuv

In this section, we model the multi-band LCs of PTF 10iuv. In the photospheric phase, the bolometric luminosity of SNe is given by (see e.g., Arnett 1982; Chatzopoulos et al. 2012):

$$L(t) = e^{-t/\tau_d} \int_0^t L_{\text{input}}(t') e^{t'/\tau_d} dt'$$

where $L_{\text{input}}(t)$ is the instantaneous power input, τ_d is the diffusion timescale (Arnett 1982), κ is the optical opacity of the ejecta with values in the range of 0.025–0.25 cm^2 g^{-1} (see, e.g., Mazzali et al. 2001), v_{ph} is the photospheric velocity of the SN, c is the speed of light, and M_{ej} is the ejecta mass. We assume that the early photosphere expansion velocity (v_{ph}) of PTF 10iuv is a constant (10,000 km s^{-1}; Kasliwal et al. 2012). In the nebular phase, the bolometric luminosity of an SN is just the instantaneous power input, i.e., $L(t) = L_{\text{input}}(t)$. We note that Arnett (1982) does not consider the γ-ray leakage effect, while all the input functions we use do account for this.

We assume that the photosphere evolution can be described by the blackbody model. As shown in Figure 1 [Figure 1: see original paper], the spectral energy distributions (SEDs) of PTF 10iuv at all epochs with photometry in at least three bands can be described by the blackbody model. This indicates that the blackbody assumption is valid at these epochs. Furthermore, we assume that the late-time temperature (T_f) is a constant (the temperature floor; Nicholl et al. 2017).

2.1. The 56Ni Model

We first use the 56Ni cascade decay model, which is widely adopted to model the LCs of normal SNe Ib and Ic, to fit the multi-band LCs of PTF 10iuv. The power input function ($L_{\text{input}}(t)$) of 56Ni cascade decay is from Valenti et al. (2008). In the 56Ni model, the γ opacity (κ_γ) and positron opacity (κ_{e^+}) of the SN ejecta are set to be 0.027 and 7 cm^2 g^{-1}, respectively (e.g., Cappellaro et al. 1997; Mazzali et al. 2000; Maeda et al. 2003).

The definitions, units, and prior ranges of the free parameters of the 56Ni model are listed in Table 1 (columns 1–4). To obtain the best-fitting values and 1σ ranges of the parameters, we use the Markov Chain Monte Carlo (MCMC) method by executing the emcee Python package (Foreman-Mackey et al. 2013).

The fit of the 56Ni model is shown in Figure 2 [Figure 2: see original paper]; the corresponding corner plot is presented in the upper panel of Figure A1. The medians, 1σ ranges, and best-fitting values of the parameters are listed in Table 1 (column 5). We find that the 56Ni model fails to fit the LCs of PTF 10iuv, since the flux of the long plateau (138.8–290.3 days after the first data point) in the r-band is higher than that produced by the 56Ni model.

Assuming that the flux of the last two data points is from the host galaxy and subtracting it from all r-band data (as in Kasliwal et al. 2012), we find that the 56Ni model can fit the r-band LC of PTF 10iuv well (see Figure 2 [Figure 2: see original paper]; the corresponding corner plot is presented in the lower panel of Figure A1; the medians, 1σ ranges, and best-fitting values of parameters are listed in column 6 of Table 1). However, the derived $M_{\rm ej}$ is $4.22^{+0.35}_{-0.73}$ M ; though this is lower than the value ($6.862^{+0.898}_{-0.350}$ M) derived by the same model for the multi-band LCs of PTF 10iuv, it is significantly larger than 2.8 M , which is twice the Chandrasekhar mass and can be regarded as the upper limit for any WD-WD binary system. This indicates that PTF 10iuv might be a CCSN from the explosion of a massive star.

However, almost all confirmed CCSNe are not found in elliptical galaxies. This, together with the fact that the distance between PTF 10iuv and its potential host galaxy (which is an elliptical galaxy) is very large (37 kpc), and that the spectra of PTF 10iuv are different from those of typical SNe Ib, disfavors the scenario that PTF 10iuv is a CCSN. A larger value of would reduce $M_{\rm ej}$, but the larger leakage effect would result in a worse fit. This indicates that the assumption that the late-time flux was from the host galaxy cannot alleviate the problem of the 56Ni model for fitting the LCs of PTF 10iuv. To fit the LCs of PTF 10iuv, more complicated models must be constructed. We no longer consider the possibility of host-galaxy contamination below.

2.2. The Four-element Model

The second possibility for the late-time excesses of the LCs of PTF 10iuv is that they originated from the cascade decay of 44Ti, a long-lived radioactive element. In this scenario, the late-time LCs were mainly powered by 44Ti and 56Ni. As demonstrated by observations and numerical simulations, other radioactive elements (e.g., 52Fe, 48Cr, 44Ti) should also be produced by Ca-rich SNe, and their contributions might exceed that of 56Ni cascade decay at some epochs.

The numerical simulations of Waldman et al. (2011) include seven radioactive elements. To reduce the number of free parameters, we neglect contributions from three elements (57Ni, 51Mn, and 49Cr), and generalize the 56Ni model to one including four elements (56Ni, 52Fe, 48Cr, and 44Ti). In this model, we expect that the early-time LCs are mainly powered by 56Ni, 48Cr, and 52Fe, while the late-time LCs are mainly powered by 44Ti.

The power input function of the four-element model includes contributions from

56Ni, 52Fe, 48Cr, and 44Ti. The input function of 44Ti is from Equation (1) of Timmes et al. (1996); the value of κ_γ for 44Ti is fixed at 0.04 cm^2 g^{-1} (Timmes et al. 1996; Seitenzahl et al. 2014). The input functions of 52Fe and 48Cr are from equation (16) of Seitenzahl et al. (2014), with κ_γ fixed at 0.027 cm^2 g^{-1} (Waldman et al. 2011). The values of the half-life ($t_{1/2}$), the total energy radiated in gamma-rays Q_γ, and the total energy liberated in the form of particles $Q_{\rm th}$ for 52Fe, 48Cr, and 44Ti are from Tables 3 and 4 of Dessart et al. (2014). The lifetime (τ) of 48Cr and 44Ti can be calculated accordingly. The definitions, units, and prior ranges of the free parameters of the four-element model are listed in Table 2 (columns 1–4).

We find that the four-element model can fit the LCs of PTF 10iuv (see Figure 3 [Figure 3: see original paper]). The medians, 1σ ranges, and best-fitting values of the parameters are listed in Table 2 (column 5); the corresponding corner plot is presented in Figure A2. The derived parameters of the four-element model are $M_{\rm ej} = 1.52^{+0.25}_{-0.25}$ M , $M_{\rm Ni} = 0.032^{+0.002}_{-0.002}$ M , $M_{\rm Ti} = 0.244^{+0.018}_{-0.018}$ M , $M_{\rm Cr} = 0.0004^{+0.045}_{-0.0004}$ M , $M_{\rm Fe} = 0.045^{+0.001}_{-0.045}$ M , $\kappa = 0.086^{+0.068}_{-0.013}$ cm^2 g^{-1}, $T_{\rm floor} = 3405.491^{+3748.707}_{-83.315}$ K, $t_{\rm shift} = -0.894^{+1.617}_{-0.155}$ days. The value of χ^2/dof is 1.831. Using the best-fitting parameters, we can reproduce the theoretical bolometric LC of PTF 10iuv and derive the rise time t_p (13.90 days) and the peak luminosity L_p (8.15 × 10^{41} erg s^{-1}). The derived kinetic energy E_k ($E_{\rm ej}$) of PTF 10iuv is 4.31 × 10^{50} erg.

2.3. The 56Ni Plus CSI Model

Another promising scenario that can account for the late-time excesses in photometry involves interaction between the ejecta and the circumstellar medium (CSM). In this scenario, the SN ejecta collide with the CSM, producing forward and reverse shocks that convert a fraction of the kinetic energy of the ejecta to ultraviolet (UV)-optical-infrared (IR) radiation. The circumstellar interaction (CSI) provides additional energy sources for the SNe and increases their luminosity. The details of the CSI model can be found in Wang et al. (2019), which is based on Chevalier (1982), Chevalier & Fransson (1994), and Chatzopoulos et al. (2012). We assume that the photosphere expanded at early-time epochs. The density profile of the CSM can be described by $\rho_{\rm CSM} = qr^{-s}$, where $q = \rho_{\rm CSM,1} r_1^s$, r_1 is the innermost radius of the CSM, and $\rho_{\rm CSM,1}$ is the density of the CSM at r_1. The CSM is a shell or a stellar wind when $s = 0$ or $s = 2$.

The fit using the four-element model shows that the early-time LCs are mainly powered by the cascade decay of 56Ni, and the contributions of other radioactive species can be neglected. Therefore, we assume that the early-time LCs were powered by the cascade decay of 56Ni, while the late-time LCs were mainly powered by the CSI triggered a few days after the explosion. The contributions of other radioactive elements are neglected. The definitions, units, and prior ranges of the free parameters for the 56Ni plus CSI model are listed in Table 3 (columns 1–4).

We find that the 56Ni plus CSI model can fit the LCs of PTF 10iuv (see Figure 4 [Figure 4: see original paper]). The medians, 1σ ranges, and best-fitting values of the parameters for the cases of $s = 0$ and $s = 2$ are listed in Table 3 (columns 5 and 6); the corresponding corner plots are presented in Figures A3 and A4. The derived parameters of the 56Ni plus CSI model for the case of $s = 0$ ($s = 2$) are $M_{\rm ej} = 2.102^{+0.035}_{-0.334}$ M ($0.782^{+0.036}_{-0.325}$ M), $M_{\rm Ni} = 0.490^{+0.057}_{-0.054}$ M ($0.640^{+0.161}_{-0.074}$ M), $M_{\rm CSM} = 0.555^{+0.162}_{-0.270}$ M ($0.408^{+0.023}_{-0.108}$ M), $\rho_{\rm CSM,1} = 42.794^{+46.001}_{-10.008} \times 10^{-15}$ g cm^{-3} ($1.280^{+0.642}_{-0.642} \times 10^{-15}$ g cm^{-3}), $t_{\rm diff} = 92.470^{+10.008}_{-1.546}$ days ($38.085^{+83.315}_{-1.634}$ days), $\epsilon = 0.333^{+0.068}_{-0.013}$ ($0.162^{+0.013}_{-0.023}$), $r_1 = 0.086^{+0.068}_{-0.013}$ ($0.057^{+0.013}_{-0.013}$), $\kappa = 0.025^{+0.068}_{-0.013}$ cm^2 g^{-1} ($0.025^{+0.013}_{-0.013}$ cm^2 g^{-1}), $T_{\rm floor} = 3332.641^{+3748.707}_{-83.315}$ K ($3759.749^{+3748.707}_{-83.315}$ K), and $t_{\rm shift} = -1.546^{+1.617}_{-0.155}$ days ($-1.634^{+1.617}_{-0.155}$ days). The values of χ^2/dof for the two cases are 2.419 and 1.938, respectively.

The $M_{\rm CSM}$ derived is 0.3 or 0.4 M . As shown in Dan et al. (2011), for a 0.5 and 1.2 M WD system, only 3% of the mass of the secondary star (i.e., 0.015 M) is ejected from the merger. This fraction can be enhanced to 10% (i.e., 0.05 M ; Guerrero et al. 2004). The amount of CSM derived here is at least 10 times that from these two values, indicating that this model is disfavored. Moreover, the absence of Hα emission lines in the nebular phases (Kasliwal et al. 2012) indicates that the CSM must be hydrogen-poor. Assuming that the CSM originated from a helium-rich companion via accretion or merger, the interaction between the ejecta and this amount of helium-rich CSM would produce helium emission lines. However, Kasliwal et al. (2012) do not report helium emission lines in the spectra. These findings suggest that it is difficult for the 56Ni plus CSI model to account for the LCs of PTF 10iuv.

3. Discussion

3.1. The Nucleosynthesis and Main Energy Sources of PTF 10iuv

The derived $M_{\rm ej}$ of PTF 10iuv using the 56Ni model is $6.898^{+0.898}_{-0.350}$ M (for multi-band fit) or $4.22^{+0.35}_{-0.73}$ M (for r-band fit). Both values are significantly larger than the total masses of a WD-WD binary system, favoring the massive star explosion scenario. However, Section 2.1 demonstrates that the massive star scenario is disfavored. Additionally, the 56Ni plus CSI model is also disfavored. Therefore, we no longer discuss these two models.

The derived $M_{\rm Ni}$ is 0.031 M , twice the value (0.016 M) derived by Kasliwal et al. (2012). The derived $M_{\rm Fe}$ and $M_{\rm Cr}$ are 0.046 M and 0.001 M , respectively. The masses of 56Ni and 48Cr are roughly consistent with the numerical results of models CO.55HE.2 and CO.6HE.2 in Waldman et al. (2011) (see the last columns of their Table 2). However, the models in Waldman et al. (2011) suppose that only the helium shells are ejected, while our derived $M_{\rm ej}$ favors the scenario in which the carbon-oxygen (CO) WD is also blown up.

Although the derived $M_{\rm Fe}$ is slightly larger than $M_{\rm Ni}$, the contribution of 52Fe is significantly lower than that of 56Ni. This is because the lifetimes of 52Fe (0.498

days) and 52Mn (0.022 days) are significantly shorter than those of 56Ni (8.764 days) and 56Co (111.424 days). The contribution of 48Cr is also significantly lower than that of 56Ni, due to its low yield (0.001 M , which is 1/30 times M_{Ni}) and short lifetimes of 48Cr (1.296 days) and 48V (23.044 days). Therefore, the early-time LCs of PTF 10iuv were mainly powered by the cascade decay of 56Ni. For comparison, the numerical simulation using CO.45HE.2 shows that the early-time LCs of SN 2005E were mainly powered by cascade decay of 48Cr, rather than 56Ni, 52Fe, or any other radioactive element (see Figure 4 of Waldman et al. 2011).

The fact that the early-time LCs of PTF 10iuv were mainly powered by 56Ni indicates that the 56Ni model can also account for the early-time LCs of PTF 10iuv (but cannot fit the late-time LCs). Nevertheless, the four-element model is necessary, since the 56Ni model cannot constrain the masses of other radioactive species.

In the four-element model, the late-time LCs of PTF 10iuv were mainly powered by 44Ti and 56Ni. The contributions from 48Cr and 52Fe can be neglected. The 44Ti mass of the four-element model is $0.250^{+0.018}_{-0.018}$ M , which is about 1/8 the 44Ti mass (2 M) estimated by Kasliwal et al. (2012). This discrepancy might arise because Kasliwal et al. (2012) assumed that all late-time flux was from the cascade decay of 44Ti (in the scenario where the late-time flux was from 44Ti), while our model includes the contribution from 56Ni, which can reduce the required M_{Ti}.

The derived M_{Ti} is about 1.65–2 times the upper limit (0.14 M) of the numerical simulations performed for SN 2005E (Perets et al. 2010), or at least 50 times the 44Ti values (which are of order 10^{-3}–10^{-5} M) listed in Table 5 of Woosley & Kasen (2011). Subtracting the unknown host-galaxy contamination can reduce the inferred 44Ti mass. Additionally, including flux from other long-lived elements (e.g., 57Co, 55Fe, 60Co) might also reduce the required amount of 44Ti. It is reasonable to regard the derived 44Ti mass as an upper limit and assume that the real 44Ti mass is (significantly) lower than the value derived by the model.

In general, high values of M_{Ti} are required to explain the excesses relative to the LCs powered by 56Ni and other short-lived radioactive elements at 100–200 days. Another example is the numerical modeling performed by Waldman et al. (2011), which shows that 1.65 M of 44Ti is needed to explain the bolometric LC of SN 2005E 20–70 days after explosion (0.033 × 50, see model a of Figure 5 [Figure 5: see original paper] in Waldman et al. 2011 and the caption).

3.2. The Ejecta Mass and Implications for Explosion Mechanisms

The derived M_{ej} from the four-element model is $1.52^{+0.25}_{-0.25}$ M . Kasliwal et al. (2012) suppose that the rise time t_r and photospheric velocity v are 12 days and 7600 km s^{-1}, respectively, where the latter is the average photospheric velocity of PTF 10iuv. Using the relation $M_{\mathrm{ej}} \propto v t_r^2$ and comparing the M_{ej} and

v of PTF 10iuv to those of SNe Ia, they find that $M_{\rm ej}$ of PTF 10iuv is 0.46 M . By replacing 7600 km s^{-1} with the 10,000 km s^{-1} adopted here, the derived $M_{\rm ej}$ is 0.61 M , which is about half of the lower limit of our derived value.

Our derived $M_{\rm ej}$ is consistent with the ejecta mass expected from the merger of sub-Chandrasekhar WDs. Furthermore, it is larger than those of the ejected helium shells in the helium detonation scenario. This indicates that the explosion of the sub-Chandrasekhar WDs assumed to be the progenitor of PTF 10iuv left no remnant. For comparison, the numerical simulations for the bolometric LC of SN 2005E (Waldman et al. 2011) suggest that only the helium shell accreted from the companion was ejected, while the CO WD survived after the explosion.

4. Conclusions

In this paper, we model the LCs of PTF 10iuv, constraining the physical properties of its ejecta, the energy sources, and the explosion mechanisms. We find that the 56Ni model and the 56Ni plus CSI model cannot account for the photometry of PTF 10iuv, while the four-element (56Ni, 48Cr, 52Fe, and 44Ti) model can successfully fit the LCs.

In the four-element model, the early-time LCs of PTF 10iuv were mainly powered by 56Ni, and the contributions of 48Cr and 52Fe can be neglected. To explain the late-time LCs, 0.25 M of 44Ti is required. This value is rather high and can be regarded as the upper limit of the real 44Ti mass. We suggest that subtracting the unknown contributions from the host galaxy and including flux from some long-lived elements (57Co, 55Fe, 60Co) can reduce the required amount of 44Ti. Therefore, the derived 44Ti mass can be regarded as an upper limit. The derived $M_{\rm ej}$ of the four-element model is $1.52^{+0.25}_{-0.25}$ M , consistent with the ejecta mass expected from the merger of sub-Chandrasekhar WDs.

We caution that one of the assumptions of our modeling is that the SEDs of PTF 10iuv at all epochs can be described by a blackbody function. We cannot verify whether this assumption is correct at late-time epochs, since data are available in only one band (r-band). The modeling for a late-time r-band LC would be invalid if the late-time SEDs deviate from the blackbody function. This is the main caveat of our work. Additionally, possible host galaxy contamination prevents us from obtaining more accurate results.

Late-time multi-band photometric observations and detailed modeling of the LCs can provide more stringent constraints on the precise values of 44Ti mass in Ca-rich SNe. We expect that further observations of the late-time LCs of Ca-rich SNe and modeling of these observations can constrain their nucleosynthesis, energy sources, and explosion mechanisms.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC, grant Nos. 11963001, 12133003, 11833003, 11973020 (C0035736), and

U1938201). This work is also supported by the Guangxi Talent Program ("Highland of Innovation Talents").

Appendix

Figures A1–A4 display the corner plots of the fits for the LCs of PTF 10iuv using the 56Ni model, the four-element model, and the 56Ni plus CSI model, respectively.

Figure A1. The corner plots of the 56Ni model for the multi-band LCs (upper panel) and r-band LC (lower panel, where the late-time flux has been subtracted) of PTF 10iuv. The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the 1σ bounds of the parameters.

Figure A2. The corner plot of the four-element model for the multi-band LC of PTF 10iuv. The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the 1σ bounds of the parameters.

Figure A3. The corner plot of the 56Ni plus CSI model ($s = 0$). The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the 1σ bounds of the parameters.

Figure A4. The corner plot of the 56Ni plus CSI model ($s = 2$). The solid vertical lines represent the best-fitting parameters, while the dashed vertical lines represent the medians and the 1σ bounds of the parameters.

References

Aazami, A. B., & Li, W. D. 2001, IAUC, 7643, 2
Arnett, W. D. 1982, ApJ, 253, 785
Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJL, 662, L95
Cao, Y., Kulkarni, S. R., Cook, D., et al. 2015, ATel, 8428
Cappellaro, E., Mazzali, P. A., Benetti, S., et al. 1997, A&A, 328, 203
Chatzopoulos, E., Wheeler, J. C., & Vinko, J. 2012, ApJ, 746, 121
Chen, P., Dong, S., Stritzinger, M. D., et al. 2020, ApJ, 889, L6
Chevalier, R. A. 1982, ApJ, 258, 790
Chevalier, R. A., & Fransson, C. 1994, ApJ, 420, 268
Chu, J., Li, W., Kloehr, W., et al. 2007, IAUC, 8875, 2
Dan, M., Rosswog, S., Guillochon, J., & Ramirez-Ruiz, E. 2011, ApJ, 737, 89
Das, K. K., Kasliwal, M. M., Fremling, C., et al. 2023, ApJ, 959, 12
De, K., Fremling, U. C., Gal-Yam, A., et al. 2021, ApJL, 907, L18
De, K., Kasliwal, M. M., Cantwell, T., et al. 2018, ApJ, 866, 72
De, K., Kasliwal, M. M., Tzanidakis, A., et al. 2020, ApJ, 905, 58
Dessart, L., Blondin, S., Hillier, D. J., et al. 2014, MNRAS, 441, 532
Dessart, L., & Hillier, D. J. 2015, MNRAS, 447, 1370

Dimai, A., Sehgal, A., Newton, J., et al. 2005, IAUC, 8569, 1
Drout, M. R., Soderberg, A. M., Mazzali, P. A., et al. 2013, ApJ, 774, 58
Ertini, K., Folatelli, G., Martinez, L., et al. 2023, MNRAS, 526, 279
Filippenko, A. V. 1997, ARA&A, 35, 309
Filippenko, A. V., Chornock, R., Swift, B., et al. 2003, IAUC, 8159, 2
Foley, R. J. 2015, MNRAS, 452, 2463
Foreman-Mackey, D., Hogg, D. W., Lang, D., et al. 2013, PASP, 125, 306
Gal-Yam, A. 2017, Handbook of Supernovae (Cham: Springer), 195
Graham, J., Li, W., Trondal, O., et al. 2005, IAUC, 8467, 1
Guerrero, J., García-Berro, E., & Isern, J. 2004, A&A, 413, 257
Irani, I., Prentice, S. J., Schulze, S., et al. 2022, ApJ, 927, 10
Irani, I., Chen, P., Morag, J., et al. 2024, ApJ, 962, 109
Jacobson-Galán, W. V., Margutti, R., Kilpatrick, C. D., et al. 2020b, ApJ, 898, 166
Jacobson-Galán, W. V., Polin, A., Foley, R. J., et al. 2020a, ApJ, 896, 165
Jacobson-Galán, W. V., Margutti, R., Kilpatrick, C. D., et al. 2021, ApJ, 908, L32
Kasliwal, M. M., Kulkarni, S. R., Gal-Yam, A., et al. 2012, ApJ, 755, 161
Kawabata, K. S., Maeda, K., Nomoto, K., et al. 2010, Natur, 465, 326
Leaman, J., Li, W., Chornock, R., & Filippenko, A. V. 2011, MNRAS, 412, 1419
Lee, M. G., Jang, I. S., & Kang, J. 2019, ApJ, 871, 33
Lunnan, R., Kasliwal, M. M., Cao, Y., et al. 2017, ApJ, 836, 60
Lyman, J. D., Levan, A. J., Church, R. P., et al. 2014, MNRAS, 444, 2157
Maeda, K., Mazzali, P. A., Deng, J., et al. 2003, ApJ, 593, 931
Mazzali, P. A., Iwamoto, K., & Nomoto, K. 2000, ApJ, 545, 407
Mazzali, P. A., Nomoto, K., Cappellaro, E., et al. 2001, ApJ, 547, 988
Moriya, T. J., Mazzali, P. A., Tominaga, N., et al. 2017, MNRAS, 466, 2085
Nicholl, M., Guillochon, J., & Berger, E. 2017, ApJ, 850, 55
Perets, H. B., Gal-Yam, A., Mazzali, P. A., et al. 2010, Natur, 465, 322
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Prentice, S. J., Maguire, K., Flörs, A., et al. 2020, A&A, 635, A186
Puckett, T., & Dowdle, G. 2000, IAUC, 7507, 2
Puckett, T., Toth, D., Schwartz, M., et al. 2003, IAUC, 8117, 1
Pugh, H., & Li, W. 2003, IAUC, 8113, 2
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Seitenzahl, I. R., Timmes, F. X., & Magkotsios, G. 2014, ApJ, 792, 10
Shen, K. J., & Bildsten, L. 2009, ApJ, 699, 1365
Shen, K. J., Kasen, D., Weinberg, N. N., et al. 2010, ApJ, 715, 767
Sullivan, M., Kasliwal, M. M., Nugent, P. E., et al. 2011, ApJ, 732, 118
Taubenberger, S. 2017, Handbook of Supernovae (Cham: Springer), 317
The, L.-S., Clayton, D. D., Diehl, R., et al. 2006, A&A, 450, 1037
Timmes, F. X., Woosley, S. E., Hartmann, D. H., et al. 1996, ApJ, 464, 332
Valenti, S., Benetti, S., Cappellaro, E., et al. 2008, MNRAS, 383, 1485
Valenti, S., Yuan, F., Taubenberger, S., et al. 2014, MNRAS, 437, 1519
Waldman, R., Sauer, D., Livne, E., et al. 2011, ApJ, 738, 21

Wang, L. J., Wang, X. F., Cano, Z., et al. 2019, MNRAS, 489, 1110
Woosley, S. E., & Kasen, D. 2011, ApJ, 734, 38
Zenati, Y., Perets, H. B., Dessart, L., et al. 2023, ApJ, 944, 22

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.