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The Helium Common-envelope Wind Scenario for SN 2020eyj

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Abstract

SN 2020eyj is the first Type Ia supernova (SN Ia) showing the signature of compact helium-rich circumstellar material (CSM). Such a large amount of CSM is difficult to explain in a single-degenerate scenario where the donor star is a helium star. Here we show that, under certain conditions, it is possible that the transfer of helium leads to a common envelope (CE) engulfing the system, similar to the CE wind model proposed by X. Meng & P. Podsiadlowski. If in such a helium CE wind model the initial white dwarf mass is larger than 1.1 $M_\odot$ and the helium star is more massive than 1.8 $M_\odot$, the mass of a helium CE can be larger than 0.3 $M_\odot$ prior to supernova explosion. The CE mass heavily depends on the initial parameters of the binary system. A dynamical CE ejection event could occur shortly before the supernova, and then our model may naturally explain the properties of SN 2020eyj, specifically the massive He-rich CSM, and its dim peak brightness, low ejecta velocity, and low birth rate.

Unified Astronomy Thesaurus concepts: Type Ia supernovae (1728); Supernova remnants (1667); White dwarf stars (1799)

1. Introduction

Although Type Ia supernovae (SNe Ia) are very important in cosmology (e.g., A. Riess et al. 1998; S. Perlmutter et al. 1999), their exact origin is still unclear, and many potential progenitor models have been proposed (B. Wang & Z. Han 2012; D. Maoz et al. 2014; N. Soker 2019a; P. Ruiz-Lapuente 2019; Z.W. Liu et al. 2023; N. Soker 2024a; A. J. Ruiter & I. R. Seitenzahl 2025). While such models enjoy a degree of empirical support, they are still simultaneously confronted with substantial problems, both from theoretical and observational perspectives (D. A. Howell 2011; D. Maoz et al. 2014; S. W. Jha et al. 2019). Recently, a unique SN Ia, SN 2020eyj, showing a delayed interaction with a large amount of helium-rich circumstellar material (CSM) has been reported, which provides an unusual opportunity to constrain the progenitor system of a particular SN Ia (E. C. Kool et al. 2023). Using the optically thick wind (OTW) model (I. Hachisu et al. 1996), E. C. Kool et al. (2023) suggested that SN 2020eyj originated from a single degenerate (SD) system consisting of a white dwarf (WD) + helium star. However, N. Soker & E. Bear (2023) subsequently challenged some of the arguments in E. C. Kool et al. (2023) and proposed that this supernova is from a version of the core-degenerate (CD) channel, in which two major common-envelope (CE) phases occurred and the supernova was the product of the merger of a WD and the core of a helium red giant.

E. C. Kool et al. (2023) describe the main properties of SN 2020eyj in detail; here, we list the ones that are most relevant for our study. (1) The most remarkable feature is that the supernova shows clear signatures of helium-rich CSM with which the supernova ejecta interact. Before the interaction, the light curve is similar to a normal SN Ia, but with a lower ejecta velocity and a lower peak brightness. These properties may indicate an SN Ia from an initially massive carbon–oxygen (CO) or hybrid carbon–oxygen–neon (CONe) WD (K. Nomoto et al. 2003; X. Meng & P. Podsiadlowski 2018). (2) During the interaction phase, the spectra show many similarities to the SN Ia–CSM, PTF 11kx, but with strong helium emission lines (B. Dilday et al. 2012; J. M. Silverman et al. 2013). The CSM interaction in SN 2020eyj is also confirmed by the detection of a radio counterpart, which can be explained either by a 0.3–1.0 $M_\odot$ CSM in a wind model or 0.36 $M_\odot$ CSM in a shell model within 10^{17} cm of the supernova.

N. Soker et al. (2013) argued that the canonical SD model cannot account for such a large amount of CSM around PTF 11kx. Similarly, the canonical SD system of a WD + a helium star cannot explain the amount of CSM in the case of SN 2020eyj, especially for the wind case considered in E. C. Kool et al. (2023; see also N. Soker & E. Bear 2023). For the wind model in E. C. Kool et al. (2023), the mass-transfer rate before the supernova explosion would have to be at least $10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$, and possibly as high as $3\times10^{-2}\,M_\odot\,\mathrm{yr}^{-1}$, which seems impossible for binary evolution models (B. Wang et al. 2009a; T. J. Moriya et al. 2019). The reason for such a high inferred mass-transfer/mass-loss rate is that in the OTW model the wind velocity is higher than $1000\,\mathrm{km\,s^{-1}}$ (I. Hachisu et al. 1996; T. J. Moriya et al. 2019). However, many predictions from the OTW model are not confirmed by other observations (see X. Meng & P. Podsiadlowski 2017 for detailed discussions). E. C. Kool et al. (2023), also realizing these problems, therefore suggested that there could be a long-lived disk around the progenitor system, which may however raise other problems (see the discussion in N. Soker & E. Bear 2023).

X. Meng & P. Podsiadlowski (2017) constructed a new version of the SD model, the common-envelope wind (CEW) model, which can explain the large amount of CSM around SNe Ia–CSM (see also X. Meng & P. Podsiadlowski 2018 and

N. Soker 2019b) and avoids the mass-transfer rate problem in E. C. Kool et al. (2023). In particular, the wind velocity is lower than 100 km s^{-1} in the CEW model, similar to that in the CD model (Y. Cui et al. 2022). In this paper, based on detailed binary evolution calculations of WD + He star systems, we will show that in such systems a helium CE can form just as in the CEW model and has the potential to explain the properties of SN 2020eyj, if there still is a massive CE around the progenitor system at the time of the explosion (which we will refer to as a HeCEW model).

The paper is organized as follows. In Section 2, we describe our method and present the results of the calculations in Section 3. We discuss the results and present our main conclusions in Section 4.

2. Method

The basic description of the helium common-envelope wind (HeCEW) model here is similar to the CEW model in X. Meng & P. Podsiadlowski (2017), except that the companion is a helium star. We do not repeat the details here and just describe the differences. We calculate the binary evolution of WD + He star systems, where the mass transfer from the companions to the WDs may begin when the companions are on the helium main sequence (MS) or in the helium Hertzsprung gap (HG). Here, orbital angular momentum loss by gravitational wave radiation is included by adopting the standard formula from L. D. Landau & E. M. Lifshitz (1971).

For a binary system consisting of a WD + a He star, after the He star fills its Roche lobe, a phase of Roche lobe overflow (RLOF) occurs and the helium star transfers helium-rich material onto the surface of the WD, which then increases its mass. If the WD mass grows to 1.378 $M_{\odot}$, we assume that the WD explodes as an SN Ia (K. Nomoto et al. 1984).

The mass-growth rate of the WD is calculated as follows. (1) If the mass-transfer rate from the helium companion to the WD exceeds a critical accretion rate, $\dot{M}_{\rm cr}$, we assume a CE forms around the binary system and that the WD increases its mass according to $\dot{M}_{\rm WD} = \dot{M}_{\rm cr}$, where the method to calculate the $M_{\rm CE}$ is the same as that in X. Meng & P. Podsiadlowski (2017). The critical accretion rate is given by K. Nomoto (1982) as

$$\dot{M}_{\rm cr} = 7.2 \times 10^{-6}(M_{\rm WD}/M_{\odot} - 0.6)\, M_{\odot}\ {\rm yr}^{-1}. \quad (1)$$

(2) If the CE disappears, the mass-growth rate of the WD is given by

$$\dot{M}_{\rm WD} = \eta_{\rm He}|\dot{M}_2|, \quad (2)$$

where $\eta_{\rm He}$ is taken from M. Kato & I. Hachisu (2004). Then, the WD may explode with or without a CE. If the CE mass is more massive than 0.3 $M_{\odot}$ when $M_{\rm WD} = 1.378\ M_{\odot}$, we assume that this explosion is a candidate system for SN 2020eyj. Actually, the observational signature of the interaction between the supernova ejecta and the helium-rich CSM does not clearly emerge until approximately 50 days after the explosion. This necessarily requires that a CE ejection took place before the supernova explosion to form a gap between the progenitor system and the dense CSM. We will discuss this in Section 4.

A relatively massive initial WD possesses a lower carbon abundance. This results in a lower production of ^{56}Ni during the SN Ia explosion, leading to a lower peak luminosity (K. Nomoto et al. 2003; X. Meng & W. Yang 2011). Therefore, the relatively dim peak brightness of SN 2020eyj may imply that it originated from a relatively massive initial WD. Since a hybrid CONe WD could produce an SN Ia–CSM (X. Meng & P. Podsiadlowski 2018), we assume here that the initial WDs leading to SNe Ia could be as massive as 1.3 $M_{\odot}$ and therefore set the initial WD mass to 1.1, 1.2, and 1.3 $M_{\odot}$, respectively. The initial masses of the donor stars, M_2^i, range from 1.5 to 3.4 $M_{\odot}$ in steps of 0.1 $M_{\odot}$; the initial orbital periods, P^i, are taken from the range of $\log(P^i/{\rm d}) = -1.2$ to 1.3 in steps of 0.1. Our parameter space is smaller than in B. Wang et al. (2009a), as we restrict it to the range where the WD can potentially explode inside a CE.

3. Results

Figure 1 shows the evolution of the key binary parameters from a WD + He star system, as well as the evolutionary track of the donor star in the Hertzsprung–Russell diagram and the evolution of the orbital period. In this example, the initial system has a donor of $M_2^i = 2.8\ M_{\odot}$, a WD of $M_{\rm WD}^i = 1.2\ M_{\odot}$, and an initial orbital period of $\log(P^i/{\rm d}) = -0.9$. Actually, the binary evolution here is similar to that shown in B. Wang et al. (2009a), although the basic physical picture is different (see also X. Meng & P. Podsiadlowski 2017). The companion fills its Roche lobe in the helium HG, i.e., the system experiences case BB RLOF. The mass-transfer rate exceeds $\dot{M}_{\rm cr}$ soon after the onset of RLOF, and then a CE forms around the binary system, where a part of the CE material is lost from the surface of the CE. Because the mass-transfer rate is generally higher than $\dot{M}_{\rm WD} + \dot{M}_{\rm loss}$, the CE mass increases to a value exceeding 0.5 $M_{\odot}$. After 3.6 × 10^4 yr, the WD increases its mass to 1.378 $M_{\odot}$, where it explodes. At this stage, the mass-transfer rate is still higher than $\dot{M}_{\rm cr}$, and the CE has a mass of 0.5344 $M_{\odot}$. Such a CE is massive enough to explain the large CSM around SN 2020eyj.

Figure 2 shows the final outcomes of all the binary evolution calculations for different initial WD masses in the $M_{\rm CE}$–$M_2^{\rm SN}$ plane. The figure clearly shows that, at the moment when $M_{\rm WD} = 1.378\ M_{\odot}$, many models have a CE with a mass larger than 0.3 $M_{\odot}$, where the largest mass is 0.78 $M_{\odot}$. The figure also shows that the more massive the initial WD, the larger the parameter space fulfilling the CSM constraint for SN 2020eyj. Probably any system with $M_{\rm CE}$ larger than ~0.1 $M_{\odot}$ when $M_{\rm WD} = 1.378\ M_{\odot}$ would look like an SN Ia–CSM. In addition, similar to Figure 18 in X. Meng & P. Podsiadlowski (2017), there seems to be a gap between $M_{\rm CE} = 10^{-3}\ M_{\odot}$ and $10^{-2}\ M_{\odot}$, which originates from different evolutionary stages of the companion stars at the onset of RLOF, which sets the mass-transfer timescale (see details in X. Meng & P. Podsiadlowski 2017).

Figure 3 shows how the CE mass at the time of the supernova depends on the initial binary parameters for the case of $M_{\rm WD}^i = 1.3\ M_{\odot}$, for which the initial parameter space for SN 2020eyj is the largest. The figure shows that, for fixed initial WD mass and fixed initial orbital period, the CE mass at the time of the supernova increases with the initial companion mass. For a companion mass more massive than 1.8 $M_{\odot}$, the explosion can produce the required properties to explain SN 2020eyj. Similarly, for the system with a given initial WD mass and a given companion mass, the CE mass at the time of the supernova generally increases with the initial orbital period. To produce an SN 2020eyj–like supernova, the initial

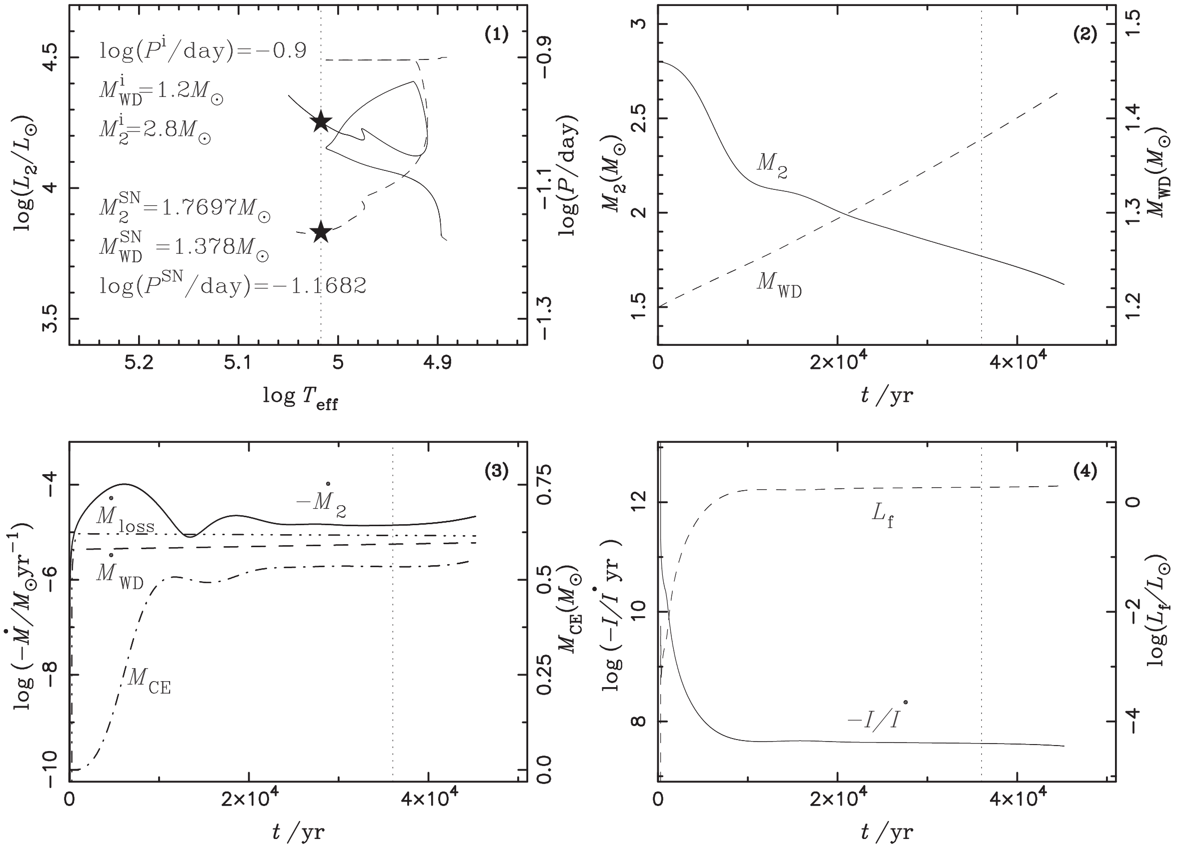

Figure 1. Illustrative binary evolution calculation in the HeCEW model. The evolution of various parameters is shown, including the WD mass, $M_{\rm WD}$, the secondary mass, M_2, the mass-transfer rate, $\dot{M}_2$, the mass-growth rate of the WD, $\dot{M}_{\rm WD}$, the mass of the CE, $M_{\rm CE}$, the mass-loss rate from the system, $\dot{M}_{\rm loss}$, the frictional luminosity, $L_{\rm f}$, and the merger timescale for the binary system, $-I/\dot{I}$, as labeled in each panel. The evolutionary track of the donor star and the evolution of the orbital period are shown as solid and dashed curves in panel (1), respectively. Dotted vertical lines in all panels and asterisks in panel (1) indicate the position where the WD is expected to explode as an SN Ia. The initial and the final binary parameters are given in panel (1).

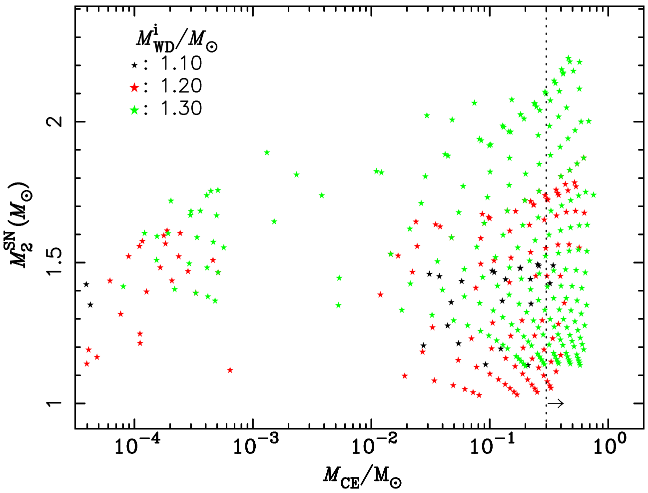

Figure 2. The CE mass and the companion mass when $M_{\rm WD} = 1.378\ M_\odot$ for different initial WD masses. The vertical dotted line shows the lower limit for the amount of CSM around the progenitor of SN 2020eyj.

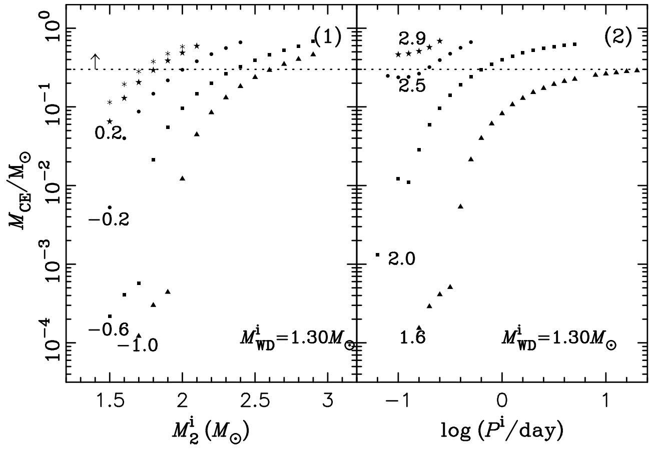

Figure 3. The CE mass as a function of the initial companion mass when $M_{\rm WD} = 1.378\ M_\odot$ for $M^i_{\rm WD} = 1.3\ M_\odot$. The horizontal dotted line shows the lower limit for the amount of CSM required around the progenitor of SN 2020eyj.

period should be longer than $\log(P^i/{\rm d}) = -1.0$, and could be as long as $\log(P^i/{\rm d}) = 1.3$, for the case of $M^i_{\rm WD} = 1.3\ M_\odot$.

For our HeCEW model, a large amount of helium-rich material may be lost from the CE surface to form the CSM, and the total amount could be as massive as $\sim 1\ M_\odot$, lower than that from the WD + MS channel by a factor of ~ 3 (X. Meng & P. Podsiadlowski 2017). Except for the helium lines in the spectra, such CSM may also form dust and cause light echoes (X. Wang et al. 2008; Y. Yang et al. 2017). We can simply calculate the maximum distance that the lost material will have reached when $M_{\rm WD} = 1.378\ M_\odot$ by $d = v_{\rm W} \times t_{\rm d}$, where $v_{\rm W}$ is the wind velocity of the material lost, and $t_{\rm d}$ is the delay time from the onset of mass transfer to the time of the supernova. Assuming a wind velocity of 50 km s^{-1}, a plausible value for the wind from a He CE, the maximum

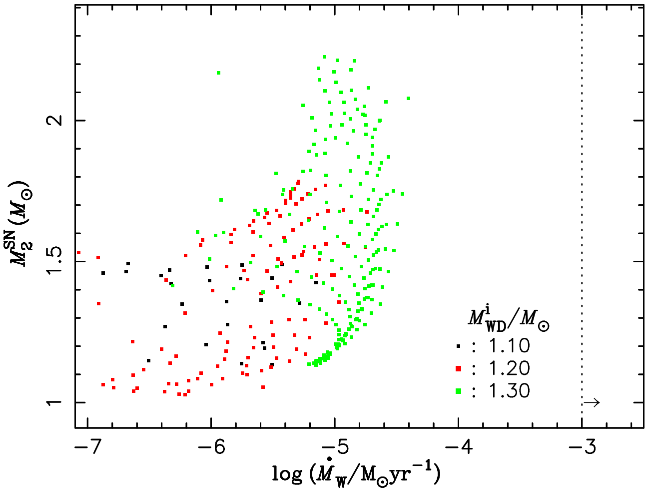

Figure 4. The wind mass-loss rate and the companion mass when $M_{\rm WD} = 1.378\,M_\odot$ for different initial WD masses. The vertical dotted line shows the lower limit of the wind mass-loss rate for the progenitor of SN 2020eyj if the OTW model were adopted.

distance derived here is shorter than that for WD + MS systems reported by X. Meng & P. Podsiadlowski (2017) by a factor of about 80. This difference stems primarily from the difference in the mass-growth rates of the WD between the WD + He star and WD + MS channels. Specifically, the mass-growth rate during the CE phase in the WD + He star channel is roughly 7 times higher than that in the WD + MS channel. An additional reason is that, in this study, we only consider the systems with relatively massive companions, in which all WDs explode during the CE phase. In contrast, X. Meng & P. Podsiadlowski (2017) focused on systems that may contain less massive MS companions, allowing the WDs to explode in the so-called recurrent nova phase, corresponding to a mass-transfer timescale on the order of a few 10^6 yr. These two reasons lead to a significantly shorter delay time ($t_{\rm d}$) for the WD + He star systems examined in this work compared to the WD + MS ones in X. Meng & P. Podsiadlowski (2017).

4. Discussions and Conclusions

This work was motivated by the discovery of SN 2020eyj, an SN Ia–CSM with a large amount of helium-rich CSM (E. C. Kool et al. 2023). Although E. C. Kool et al. (2023) favor the SD scenario, some of the detailed physical aspects may be problematic. For example, based on the OTW model they adopted, the mass-loss rate needed would have to be higher than $10^{-3}\,M_\odot\,{\rm yr}^{-1}$, and possibly as high as $3 \times 10^{-2}\,M_\odot\,{\rm yr}^{-1}$. Figure 4 shows estimates for the wind mass-loss rate and the companion mass when $M_{\rm WD} = 1.378\,M_\odot$ for different initial WD masses for the OTW model, where $\dot{M}_{\rm W} = |\dot{M}_2| - \dot{M}_{\rm WD}$.[4] The figure clearly shows that, even for the most optimistic case, the wind mass-loss rate from the OTW WD + He star scenario is lower than that needed by SN 2020eyj by a factor of ∼25–750. If the mass-loss rate is really as high as suggested by E. C. Kool et al. (2023), the system would be in a CE phase, as suggested in this paper and in N. Soker & E. Bear (2023).

In this paper, we found that, only when the initial WD is massive enough, a progenitor system consisting of a WD + a He star may produce a massive He-rich CSM, i.e., $M^i_{\rm WD} \geqslant 1.1\,M_\odot$. Considering the correlation between the initial WD mass and the peak brightness of SNe Ia (K. Nomoto et al. 2003; X. Meng & W. Yang 2011), our model may naturally explain the dim peak brightness of SN 2020eyj, as well as the low ejecta velocity. In other words, our model predicts that the SN 2020eyj–like supernovae have a relatively dim peak brightness, if the interaction between the supernova ejecta and the CSM occurs after the maximum light.

We did not carry out a detailed binary population synthesis simulation to estimate the rate of SN 2020eyj–like supernovae. However, we can get a rough estimate of the birth rate based on previous detailed calculations. The WD + He star channel may contribute to about 1%–10% of all SNe Ia (B. Wang et al. 2009b; B. Wang et al. 2017). Considering that about 1 in 100 SNe Ia explodes in a massive CE, this yields an estimate of about 0.01%–0.1% of SNe Ia belonging to the class of SN 2020eyj–like supernovae. This relative rareness may explain why only one such supernova has been observed until now.

Observations of SN 2020eyj reveal a time delay of tens of days between the supernova explosion and its subsequent interaction with the CSM, indicating the presence of a gap between its progenitor and the dense CSM. This implies the need for a merger-to-explosion delay (MED) in our model (see N. Soker 2022, 2024b for details). N. Soker & E. Bear (2023) estimate a MED of ∼10 yr for SN 2020eyj. Although the physical mechanisms responsible for forming such a gap or for the MED remain unclear (X. Meng & P. Podsiadlowski 2013; N. Soker 2022), a magnetized and rapidly rotating WD may play a role in mediating the delay (S. Justham 2011; R. Di Stefano & M. Kilic 2012; M. Ilkov & N. Soker 2012; S. Neopane et al. 2022). In our canonical CEW model, the CE is always dynamically unstable, suggesting that a CE ejection event could occur at any time prior to a supernova explosion (Y. Cui et al. 2022). Similarly, a helium-rich CE is also likely to be dynamically unstable, as in the canonical CEW scenario. A dynamical ejection event occurring shortly before the supernova could thus create the gap required by the observations of SN 2020eyj. Although a detailed dynamical simulation is necessary in the future to investigate the exact MED from the HeCEW scenario, a MED of a few years could be possible (Y. Cui et al. 2022).

In summary, we demonstrate the feasibility of the HeCEW model in explaining helium-rich SNe Ia–CSM such as SN 2020eyj. A more comprehensive and detailed investigation of the HeCEW model will be presented in future work.

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[4] The binary evolution in the OTW and CEW models is similar, although some of the physical assumptions are different. Here we use the $|\dot{M}_2| - \dot{M}_{\rm WD}$ from our HeCEW model to estimate the wind mass-loss rate from the OTW model. Such a wind mass-loss rate is slightly larger than that from the OTW due to the slightly higher $|\dot{M}_2|$.

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