

Explaining the type Ia supernova PTF 11kx with a violent-prompt merger scenario

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ABSTRACT

We argue that the multiple shells of circumstellar material (CSM) and the supernovae (SN) ejecta interaction with the CSM starting 59 days after the explosion of the Type Ia SN (SN Ia) PTF 11kx, are best described by a violent prompt merger. In this prompt merger scenario the common envelope (CE) phase is terminated by a merger of a WD companion with the hot core of a massive asymptotic giant (AGB) star. In most cases the WD is disrupted and accreted onto the more massive core. However, in the rare cases where the merger takes place when the WD is denser than the core, the core will be disrupted and accreted onto the cooler WD. In such cases the explosion might occur with no appreciable delay, i.e., months to years after the termination of the CE phase. This, we propose, might be the evolutionary route that could lead to the explosion of PTF 11kx. This scenario can account for the very massive CSM within ~ 1000 AU of the exploding PTF 11kx star, for the presence of hydrogen, and for the presence of shells in the CSM.

Key words: (stars:) supernovae: general — (stars:) supernovae: individual (PTF 11kx).

1 INTRODUCTION

Observations and theoretical studies cannot teach us yet whether all three scenarios for the formation of Type Ia supernova (SN Ia), or only one or two of them can work — e.g., Livio (2001), Maoz (2010), Howell (2011). These three basic theoretical scenarios can be described as follows. (i) In the single-degenerate (SD) scenario (e.g., Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004) a WD grows in mass through accretion from a non-degenerate stellar companion. However, the mass increase of the WD seems to be very limited (e.g., Idan et al. 2012). (ii) In the double-degenerate (DD) scenario (Webbink 1984; Iben & Tutukov 1984; see van Kerkwijk et al. 2010 for a paper on sub-Chandrasekhar mass remnants) two WDs merge after losing energy and angular momentum through the radiation of gravitational waves (Tutukov & Yungelson 1979). Some list the “double-detonation” mechanism (Woosley & Weaver 1994; Livne & Arnett 1995) as a separate channel, although it involves two WDs. (iii) In the core-degenerate (CD) sce-

nario for the formation of SN Ia the Chandrasekhar (M_{Ch}) or super-Chandrasekhar mass WD is formed at the termination of the CE phase, or during the planetary nebula phase, from a merger of a WD companion with the hot core of a massive AGB star (Kashi & Soker 2011; Ilkov & Soker 2012a; Soker 2011). The merger of a WD with the core of an AGB star was studied in the past (Sparks & Stecher 1974; Livio & Riess 2003; Tout et al. 2008). Livio & Riess (2003) suggested that the merger of the WD with the AGB core leads to a SN Ia that occurs at the end of the CE phase or shortly after, and can explain the presence of hydrogen lines. However, due to its rapid rotation (e.g., Anand 1965; Ostriker & Bodenheimer 1968; Uenishi et al. 2003; Yoon & Langer 2005; Lorén-Aguilar et al. 2009), and possibly very strong central magnetic fields (e.g., Kundu & Mukhopadhyay 2012), the explosion of a WD with $M \geq M_{\text{Ch}}$ might be substantially delayed.

The recently observed SN Ia PTF 11kx (Dilday et al. 2012) has narrow lines, including hydrogen lines, and indications of interaction with a massive circumstellar medium (CSM) which starts 59 days after the explosion. Dilday et al. (2012) argued that PTF 11kx can be explained by the SD

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scenario for SN Ia. They dismiss the merger scenario as suggested by Livio & Riess (2003) on several grounds. In particular, they claim it cannot account for several CSM shells. We find this unjustified in section 2. We further discuss the properties of the CSM in section 3, where we calculate the total radiated energy arising from the collision of the exploding gas with the CSM.

The destruction of the WD and its accretion onto the core while the core is still hot might prevent an early ignition of carbon (Yoon et al. 2007), which is one of the theoretical problems of the DD scenario (e.g., Saio & Nomoto 2004). However, in the case of PTF 11kx ignition of the merger product is required quite early, within ~ 30 yr from the CE ejection. We therefore consider in section 4 the possibility that in the case of PTF 11kx the core was destroyed onto the cooler WD. In those cases where an explosion occurs shortly after merger in the CE, there is no delay by spin-down or emission of gravitational waves. This is called a violent-prompt merger, which might be considered as a subversion of the DD and CD scenarios. In section 5 we show that in these cases a massive envelope can be ejected, and that this scenario can account for the frequency of such SN Ia. Our summary is in section 6.

2 A CASE FOR A MASSIVE CIRCUMSTELLAR MEDIUM (CSM)

Starting 59 days after the explosion of PTF 11kx, Dilday et al. (2012) detected a group of absorption lines (Na I, Fe II, Ti II, and He I) and H α and H β P-cygni lines at a velocity shift of 65 km s $^{-1}$. The Ca II H&K absorption line was detected at an outflow velocity of 100 km s $^{-1}$ and a group of emission lines (H, He, Fe, Ti) at 100 km s $^{-1}$. This, according to Dilday et al. (2012), indicates the presence of multiple CSM shells interacting with the SN ejecta. Adopting an ejecta velocity of 25 000 km s $^{-1}$ they deduced that the ejecta-CSM interaction starts at a distance of $\sim 10^{16}$ cm.

Dilday et al. (2012) suggest that PTF 11kx is a type Ia SN formed by the SD scenario. A claim that was raised also in the theoretical work of Hachisu et al. (2012). In the scenario of Dilday et al. (2012) the CSM structure is assumed to originate from recent recurrent nova eruptions whose ejecta sweep the wind of a giant companion. Based on the saturated Ca II HK absorption lines Dilday et al. (2012) calculated the CSM mass to be $M_{\text{CSM}} \simeq 5.3k M_{\odot}$, where k is the covering fraction. For the absence of an interaction with a very massive CSM, they argue that $k \ll 1$. The relevant radius of the photosphere at $t = 20$ d is $r_{\text{ph}} = 1.6 \times 10^{15}$ cm. The location of the absorbing gas according to their analysis is $r_{\text{Ca}} = 1.3 \times 10^{16}$ cm. Taking the absorbing gas to be in a torus (as they do) of larger radius r_{Ca} and smaller radius r_{ph} , the covering fraction is $k \gtrsim r_{\text{ph}}/r_{\text{Ca}} = 0.12$. We conclude, based on the analysis of Dilday et al. (2012), that $M_{\text{CSM}} > 0.6 M_{\odot}$.

We can also estimate M_{CSM} from the H α luminosity. Dilday et al. (2012) list $L_{\text{H}\alpha}$ at 5 epochs, with a maximum of $L_{\text{H}\alpha}(88 \text{ d}) = 1.84 \times 10^{40}$ erg s $^{-1}$. We take a case B recombination for solar composition gas and derive

$$M_{\text{H}\alpha} \simeq 0.2 \left(\frac{V}{10^{48} \text{ cm}^3} \right)^{1/2} M_{\odot}, \quad (1)$$

where V is a volume, and where we assumed a constant density. The volume was scaled according to the torus discussed above. If ionization is not complete then the mass could be even larger. This estimate does not depend on the calcium abundance. A value of $M_{\text{CSM}} \simeq M_{\text{H}\alpha} > 0.2 M_{\odot}$ at a distance of $\sim 10^{16}$ cm is larger than what most SD scenarios predict.

Our motivation to explore the violent-prompt merger scenario to account for a massive CSM comes from other SN Ia as well. SN 2002ic (Hamuy et al. 2003) had a strong and broad, FWHM of > 1000 km s $^{-1}$, H α emission resulting from SN ejecta-CSM interaction, with CSM mass of $\sim 6 M_{\odot}$ (Wang et al. 2004). Nomoto et al. (2005, 2004) suggested that the lightcurve can be explained by a non-spherical $\sim 1.3 M_{\odot}$ CSM. Livio & Riess (2003) proposed that SN 2002ic represents a rare subtype of the DD scenario in which the explosion occurs by core-WD merger immediately following the CE phase.

SN 2005gj is another SN Ia with hydrogen emission (Aldering et al. 2006, Prieto et al. 2007), and an aspherical or clumpy CSM (Aldering et al. 2006) with an estimated mass of $\gtrsim 0.016 - 0.16 M_{\odot}$ (Aldering et al. 2006). More emission lines of hydrogen and helium were detected with time since explosion, indicating the presence of a few CSM layers.

The multi-layer aspherical CSM in the above SNe can be explained in the frame of the violent-prompt merger scenario. (1) Before the CE phase there is the ordinary mass loss of the AGB star, but enhanced by tidal interaction. (2) During the CE ejection a spiral structure can form several shells along the line of sight, and in particular in the equatorial plane. Some numerical simulations — e.g., Ricker & Taam (2012); Sandquist et al. (1998) — show that the CE mass loss occurs in more than one episode, i.e., there are a few peaks in the mass loss rate. In particular, along each direction there can be several shells due to the spiral structure that is formed during the CE phase, and that can later have imprint in the CSM. (3) The merger process can lead to an equatorial mass loss event that ejects $\sim 0.1 - 0.5 M_{\odot}$. It can accelerate some previously ejected gas to higher velocities, e.g., ~ 100 km s $^{-1}$. (4) As observed in some post-CE planetary nebulae, e.g., Sp-1 and NGC 2346, the mass close to the star is concentrated in the equatorial plane. The rest of the mass forms a bipolar structure at much larger distances. In our model the explosion took place at the center of a pre-planetary nebulae. Our model therefore predicts that further interaction of the ejecta with the CSM will take place over the coming years to tens of years, and that the amount of accumulated mass in the CSM will be on the order of a solar mass.

3 RADIATED ENERGY

We calculate the excess energy of PTF 11kx — according to Dilday et al. (2012) — over the “normal” SN Ia SN 2002er (Jha et al. 2007). We extract the R-band light curve from Dilday et al. (2012) and integrate the luminosity as a function of time from day -7 to day 99. For PTF 11kx we take the luminosity between day 64 and day 99 to be constant, set to the value of day 64. We find that over the integrated time the energy in the R band of SN 2002er is $\sim 9.1 \times 10^{48}$ erg, and the total energy in the R band of PTF

11kx is $\sim 2.1 \times 10^{49}$ erg. Thus, in about 100 days PTF 11kx radiated $\sim 1.2 \times 10^{49}$ erg more than a typical SN Ia. As this is only the R band, the actual excess energy value can be larger. On the other hand by assuming that from day 64 to 99 the R-band luminosity does not decrease we somewhat overestimate the radiated energy. Over a period of 200 days we will take the excess energy that we attribute to the collision of the ejecta with the CSM to be $\sim 2 \times 10^{49}$ erg.

Let us take the ejecta flowing with a velocity of $v_{\text{ej}} \sim 10^4 \text{ km s}^{-1}$ to hit the CSM residing in a torus. In estimating the kinetic energy that is transferred to radiation one should consider the geometry. The CSM is in a torus rather than a spherical shell, and the shocked ejecta flows around it and cools adiabatically. The fraction of the post-shock thermal energy that will be radiated is the ratio $\eta \sim \tau_{\text{f}}/(\tau_{\text{c}} + \tau_{\text{f}})$, where τ_{c} is the radiative cooling time and

$$\begin{aligned} \tau_{\text{f}} &\simeq \frac{r_{\text{ph}}}{v_{\text{ej}}} \\ &= 2 \times 10^6 \left(\frac{r_{\text{ph}}}{2 \times 10^{15} \text{ cm}} \right) \left(\frac{v_{\text{ej}}}{10^4 \text{ km s}^{-1}} \right)^{-1} \text{ s} \end{aligned} \quad (2)$$

is the flow time scale.

For a direct shock the post-shock temperature is $T_{\text{ps}} \sim 3 \times 10^8 \text{ K}$. The post-shock density of the ejecta and the CSM have a similar electron density of $n_e \sim 10^9 \text{ cm}^{-3}$. For this temperature and density the cooling time for an optically thin gas (the optical depth over the small radius of the torus is ~ 0.1 – 0.5) is $\tau_{\text{c}} \simeq 2 \times 10^6 \text{ s}$. Thus, a fraction of $\eta \sim 0.5$ of the thermal energy will be radiated. In the collision of the ejecta with the CSM only a fraction $\zeta < 1$ of the kinetic energy of the colliding gas is transferred to thermal energy because a large area of the shock on the torus is oblique and because the CSM is accelerated and takes part of the kinetic energy. Over all, the fraction of the kinetic energy of the ejecta that is radiated is $k\eta\zeta \sim 0.05\zeta$. For a kinetic energy of 10^{51} erg this amounts to $5 \times 10^{49}\zeta$ erg. The value of ζ depends on the geometry of the CSM and how it is being changed during the interaction. The interaction should last for a time of $t_i > 1.3 \times 10^{16} \text{ cm}/v_{\text{ej}} = 150$ days. Therefore, the energy radiated within a time of 200 days can be $\sim 2 \times 10^{49}$ erg. Hence, a value of kinetic to thermal conversion ratio of $\zeta = 0.4$ can account for the observed extra luminosity.

4 ENERGY RELEASED IN THE MERGER PROCESS

4.1 The migration phase

There are various phases in the merger process (Kashi & Soker 2011). The dynamical CE phase ends when most of the envelope is ejected, and the binary system ends at an orbital separation of $\sim 1 - 3 R_{\odot}$. The gravitational energy released in this process ejects part of the envelope, and a circumbinary disk is formed by the bound material, including fall back material. This material interacts gravitationally with the binary system. Typical timescales for building-up the disk range from weeks to years, but these are gross estimates as the process requires further study. In any case, during this phase the semi-major axis is reduced to $a \simeq 0.5 - 1 R_{\odot}$, while the eccentricity increases up to

$e \lesssim 1$. Consequently, a merger can occur during this migration phase because of the substantial decrease in the periastron distance, despite the modest decrease in the semi-major axis. The merger lasts for several weeks up to a year. If the circumbinary disk is lost before the merger occurs the final evolution of the merger is driven by the emission of gravitational waves — see Fig. 7 in Kashi & Soker (2011). We note that the timescale for this will be shorter due to the high eccentricity. In any case, the merger is set up by substantially increasing the eccentricity with a very moderate decrease of the semi-major axis. This implies that during the migration phase the binary system loses an amount of energy which is approximately equal to what it has been lost during the dynamical CE phase, e.g., $\sim 10^{48}$ erg. So the total energy that is estimated to be radiated during the migration phase is $\sim 10^{48}$ erg. Moreover, the high eccentricity and monotonic increase in eccentricity imply also that the merger is likely to be violent, as required in our violent-prompt merger scenario.

This evolutionary route is different of that proposed by Chugai & Yungelson (2004) who assumed that the binary has a circular orbit. Accordingly, they argued against the post-CE merger on the ground that the spiraling-in to a distance where gravitational waves take over, $a \sim 0.03 R_{\odot}$, will release much more energy than is observed in SNe 2002ic and 1997cy. However, the migration process described above removes the objections of Chugai & Yungelson (2004) because of the modest decrease in orbital energy during it. Actually, the modest amount of released gravitational energy can be carried away by the mass ejected from the circumbinary disk and by radiation. Additionally, we note that this mass loss episode can form another circumbinary shell, with which the explosion can interact later on.

There are two possible channels to ignite the WD-core merger product: (i) A violent merger where ignition occurs within minutes (Pakmor et al. 2011, 2012a,b), and (ii) merging and relaxing within years up to the point where the WD becomes unstable and is ignited. We first note that during the merger itself more orbital gravitational energy will be released. In the first violent ignition channel there is no need to explain the additional release of gravitational energy, as it becomes part of the energy budget of the explosion. In the second channel of several years to tens of years from merger to explosion, the merger process will release energy. In section 4.2 we explain how this energy is dissipated such that the equatorial expanding gas keeps its relatively low velocity of $\sim 65 - 100 \text{ km s}^{-1}$. Basically, the released orbital energy is carried by a fast bipolar outflow and by radiation. Here we note that the ejected mass will remove angular momentum as well. Basically, the disrupted object, which in our specific case is the core of the giant, forms an accretion disk around the WD. Since the viscous timescale of this disk is much shorter than a year it plays no role in delaying the formation of a Chandrasekhar-mass remnant, that is formed within tens of years. However, viscous dissipation removes angular momentum from the disk, which must be carried away by the ejected mass. This can be done either by a disk wind or by jets, which carry all the angular momentum and a substantial fraction of the excess energy (see section 4.2).

As previously discussed, most of the left-over mass from the merger process, which is a CO-rich gas, escapes in the

form of a disk wind or jets. Thus, the circumstellar gas will have a bipolar structure, similar to that of bipolar planetary nebulae. Since in the equatorial plane there will be the torus of the hydrogen-rich gas ejected from the envelope of the giant moving slowly at velocities $\sim 100 \text{ km s}^{-1}$, the gas ejected by the explosion will first interact with it. The CO-rich gas will be ejected at much higher velocities, of the order of a few $\times 1000 \text{ km s}^{-1}$ (the escape speed from the merger remnant), and the encounter should take place much later, years to tens of years after explosion. The collision with the gas influences the lightcurve (e.g., Fryer et al. 2010).

One argument against the WD-WD merger scenario for SN Ia is that there is an early off-center ignition of carbon. However, most calculations of ignition in WD-WD merger were done for cold WDs (e.g., Kawai et al. 1987). Specifically, these authors found an early off-center carbon ignition but they consider a maximum mass accretion rate of $2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. In our scenario a much higher accretion rate is required. We actually have a process where the hot high-density core of the giant is accreted onto a more massive WD, for which there is a lack of self-consistent, realistic calculations. Future simulations, which are beyond the scope of this paper, must check whether in this situation excessive compression can be avoided, and thus prevent an early ignition of the WD. Else, the ignition in the very dense region can set the explosion itself, as in Pakmor et al. (2012b). All in all, new simulations are required to study the WD-core merger, using sophisticated three-dimensional numerical codes, because the outcome of the process is very sensitive to numerical resolution (Pakmor et al. 2012a).

It could be argued as well that traditional SN Ia carbon ignition models require the detonation to be preceded by a deflagration to occur over $\sim 1000 \text{ yr}$, which is too long for the present scenario. However, we note that in recent years other ignition channels have been discussed in the literature, e.g. ignition in sub-Chandrasekhar WDs, and the violent merger ignition (Pakmor et al. 2012b). Consequently, the ignition process must be reconsidered in the case of core-WD merger. For example, as the accreted core gas is hot an ignition might occur in an intermediate regions where temperature is high during the post-merger process.

4.2 The violent merger phase

When two WDs merge to form a super-Chandrasekhar mass WD a huge amount of energy is released. Actually, this might result in an event brighter than expected from SN Ia explosion if there is a large delay between merger and explosion. This is less of a problem in the case of the violent merger scenario (Pakmor et al. 2012b) where the explosion occurs several minutes after merger starts. In the present case, the merger is of a core of an AGB star and a WD companion (the remnant of the primary star), with masses of M_{core} and M_{WD} , respectively. Nevertheless, the merger of massive degenerate components releases less energy as they reach M_{Ch} .

The final state just before the SN Ia explosion is that the WD accreted a mass ΔM from the core, and the rest of the mass is ejected. The ejected mass carries with it energy and angular momentum. The difference in binding energy is between the energy required to unbind the core

and the gravitational energy released by the mass accreted onto the WD:

$$\Delta E_G \simeq 0.5 \frac{G(M_{\text{WD}} + 0.5\Delta M)\Delta M}{R_{\text{WD}}} - \Gamma \frac{GM_{\text{core}}^2}{R_{\text{core}}}, \quad (3)$$

where $\Gamma \simeq 0.5$ is a parameter that depends on the properties of the core. We assume an adiabatic index of $\gamma = 5/3$ as the core is hot, and take a coefficient of 0.5 in the first term of Eq. (3). The core and the WD first collide when they are on a highly eccentric orbit — see section 4.1 and Kashi & Soker (2011). This implies that the kinetic energy of the binary system must be considered. This energy is already included in the first term of Eq. (3). For the typical parameters used here the gravitational energy released is

$$\begin{aligned} \Delta E_G(\text{erg}) \simeq & 1.9 \times 10^{50} \left(\frac{M_{\text{WD}} + 0.5\Delta M}{1.3 M_{\odot}} \right) \left(\frac{\Delta M}{0.6 M_{\odot}} \right) \\ & \left(\frac{R_{\text{WD}}}{5400 \text{ km}} \right)^{-1} - 1.6 \times 10^{50} \left(\frac{\Gamma}{0.6} \right) \\ & \left(\frac{M_{\text{core}}}{1 M_{\odot}} \right)^2 \left(\frac{R_{\text{core}}}{10^4 \text{ km}} \right)^{-1}. \end{aligned} \quad (4)$$

The radius of a WD of mass $1 M_{\odot}$ is 6000 km (Provencal et al. 1998). But as matter is accreted onto the cold massive WD its radius shrinks. However, this will not release much energy as the matter in the center of the WD is relativistic, and thus the adiabatic index γ is close to the full relativistic value, $4/3$. For $\gamma = 4/3$, the marginally-stable value, no energy is released as the star contracts to satisfy hydrostatic equilibrium. Here it is not fully relativistic, but the adiabatic index is still well below $5/3$ and not much energy will be released. The binding energy of a WD at the critical mass of $1.4 M_{\odot}$ is $E_b = -5.5 \times 10^{50} \text{ erg}$ (e.g., Ibanez Cabanell 1984). For a WD merger product of mass $1.4 M_{\odot}$ and $\gamma = 5/3$ the corresponding radius is 4700 km. In summary, we conclude that not much energy will be released by the contraction of the cold accreting WD, and took an effective radius of 5400 km.

The ejected mass has more specific energy than it had before the merger. Therefore, it will carry some of the additional energy. As a large fraction of the ejected mass is blown by an accretion disk wind, it will carry angular momentum and will flow in the polar directions (and might even form two opposite jets).

Adopting typical values, the total energy that has to be radiated *before* the explosion is $E_{\text{pre}} \lesssim \text{several} \times 10^{49} \text{ erg}$. This estimate is very sensitive to the parameters due to the subtraction of two very close large values. For example, adopting $M_{\text{WD}} = 1.1 M_{\odot}$ and $\Delta M = 0.45 M_{\odot}$, and using the same formalism we find the released energy to be $\sim 10^{49} \text{ erg}$. The total energy released in radiation can be larger than that emitted during the SN explosion itself. However, the model assumes (something that, as mentioned earlier, needs verification) that the building of the merger remnant to the point it explodes lasts for several years. Therefore, the timescale is two orders of magnitudes longer than that of the SN explosion itself. The bolometric luminosity will be over one order of magnitude lower than that of the SN explosion, and most of the radiation (due to the optically thick ejected envelope) will be emitted in the IR. This is the reason why it avoided detection by different surveys in the visible. However, the model predicts that such SN

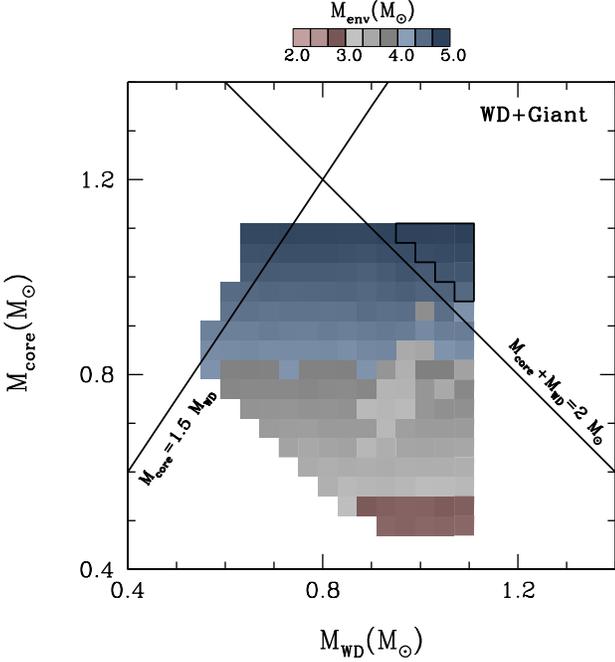


Figure 1. Mass of the envelope of the giant as a function of the mass of the primary white dwarf and of the mass of the hydrogen-exhausted core of the secondary. The different color scales denote different masses of the envelope. The brown color scale corresponds to relatively small masses of the envelope ($2 \leq M_{\text{env}}/M_{\odot} \leq 3$), the gray scale corresponds to intermediate masses ($3 \leq M_{\text{env}}/M_{\odot} \leq 4$), while the blue scale has been selected to show the masses of interest for the scenario described in the main text ($4 \leq M_{\text{env}}/M_{\odot} \leq 5$). Also plotted are the constraints given by conditions 1 and 4. For the sake of clarity, the region corresponding to the likely progenitors of PTF 11kx has been highlighted.

Ia might have a precursor lasting several years with 3–7 bolometric magnitudes fainter than the SN explosion, and peaks in the near IR. In case the merger is of a lighter core-WD system, then the pre-explosion total energy released might be much larger. But in that case the delay will be longer, as the central region needs to cool to reach the critical limit for explosion.

5 THE EVOLUTIONARY ROUTE

For the progenitor of the explosion we look for systems having the following properties.

- (i) The total mass of the secondary core during the final CE phase and the mass of the WD remnant of the primary star should be super-Chandrasekhar, $M_{\text{core}} + M_{\text{WD}} > 1.4 M_{\odot}$. But as discussed in the previous section, to prevent a pre-SN explosion outburst, the core and WD should be much more massive, $M_{\text{core}} + M_{\text{WD}} \gtrsim 2 M_{\odot}$.
- (ii) The total mass of the envelope at the final CE phase must be as massive as the observed CSM. We take it to be $M_{\text{env}} \gtrsim 2 M_{\odot}$, but prefer $M_{\text{env}} \gtrsim 4 M_{\odot}$.

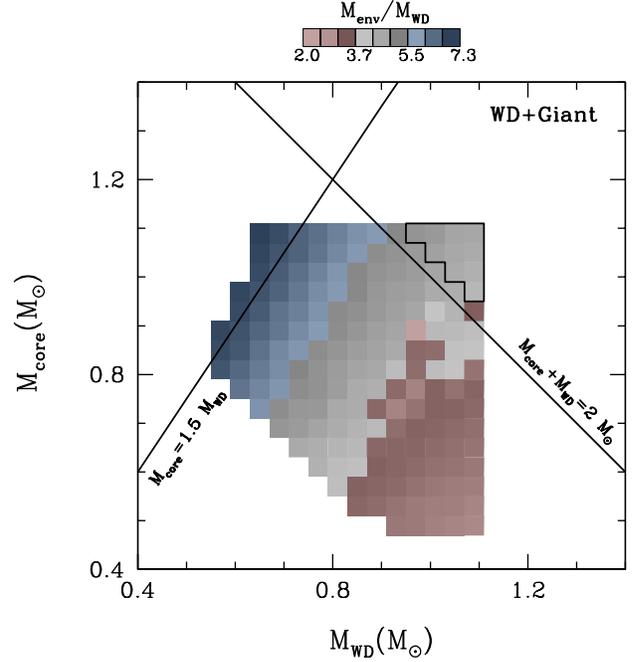


Figure 2. Ratio of the mass of the envelope of the secondary to the mass of the primary white dwarf, as given by the colored bar, as a function of the mass of the primary white dwarf and of the hydrogen-exhausted core of the secondary. The rest of the lines are the same shown in figure 1. Again, the region of likely progenitors of PTF 11kx has been conveniently highlighted in this plane.

(iii) To facilitate merger at the termination of the CE phase we require $M_{\text{env}}/M_{\text{WD}} \gtrsim 3$, but prefer a larger number even (Soker 2012).

(iv) It is likely that an explosion without a delay will take place when the core is accreted onto the cooler WD remnant of the primary star (Kashi & Soker 2011). For that the density of the core should be lower than the density of the WD. As the core is hot its radius is larger than that of a cool WD. The condition reads $M_{\text{core}} \lesssim 1.5 M_{\text{WD}}$.

(v) As we require the merger product to be a CO WD, to avoid ONe WDs, we are limited to both $M_{\text{core}} < 1.1 M_{\odot}$ and $M_{\text{WD}} < 1.1 M_{\odot}$.

To examine for such systems we ran the population synthesis code described in García-Berro et al. (2012), where all details are given. Here, for the sake of conciseness, we only present the results for systems that obey the constraints above. In figure 1 we plot the envelope mass of the secondary at the time of merger in the plane $M_{\text{core}} - M_{\text{WD}}$, while in figure 2 we present the ratio of the envelope mass to the WD mass. Note that the likely progenitors of PTF 11kx are within a region of WD masses between ~ 0.9 and $\sim 1.1 M_{\odot}$, while the masses of the hydrogen-exhausted core are also within ~ 0.9 and $\sim 1.1 M_{\odot}$. The most restrictive conditions are, respectively, conditions 1 and 3. Namely, we find that the progenitors of this supernova must fulfill that the total mass of the merged remnant should be larger than

$2 M_{\odot}$, and also that the ratio of the envelope mass to the mass of the white dwarf should be larger than ~ 3 , although other possibilities cannot be presently discarded.

Dilday et al. (2012) crudely estimate that the fraction of SNe Ia that exhibit prominent circumstellar interaction near maximum light is $\sim 0.1 - 1\%$. As $\sim 1-2$ SN Ia occur per $1000 M_{\odot}$ stars formed (Maoz et al. 2012), the estimate of Dilday et al. (2012) stands at $\sim 0.001 - 0.02$ SN Ia with massive CSM per $1000 M_{\odot}$ stars formed. Our Monte Carlo simulations show that the frequency of these systems with the conditions listed above is 0.002 per $1000 M_{\odot}$ stars formed. If we relax the assumption on the core+WD mass and the envelope mass to $M_{\text{core}} + M_{\text{WD}} \gtrsim 1.8 M_{\odot}$ (instead of $M_{\text{core}} + M_{\text{WD}} \gtrsim 2 M_{\odot}$), and $M_{\text{env}} \gtrsim 0.5 M_{\odot}$ (instead of $M_{\text{env}} \gtrsim 4 M_{\odot}$), respectively, we find 0.016 systems to obey the condition per $1000 M_{\odot}$ stars formed. The later envelope mass might be appropriate to SN 2005gj. We conclude that the violent-prompt merger scenario can satisfactorily explain all the observed properties of PTF 11kx and, moreover, that the number of expected progenitors with massive CSM is consistent with the observations.

6 SUMMARY

The conclusion that the presence of any CSM around a SN Ia implies its association with the single-degenerate (SD) scenario — e.g., Sternberg et al. (2011) — is problematic, in particular in cases where the CSM mass within ~ 1000 AU is $\gtrsim 0.01 M_{\odot}$. An explosion set by the violent-prompt merger of a WD companion with the core of the giant star naturally occurs within a massive CSM — the ejected common envelope (Livio & Riess 2003).

We find the association of the SN Ia PTF 11kx (Dilday et al. 2012) with the SD scenario to be unlikely due to the massive CSM. Instead, we found that the violent-prompt merger of a massive WD with a massive core, as marked by the thick line on the upper right corner of Figures 1 and 2, to be able to account for the properties of PTF 11kx. We predict that interaction of the ejecta with the CSM will take place over the coming decades and that the amount of mass in the CSM will be accumulated to few times of M_{\odot} . We also found from our population synthesis calculations that the number of systems with large total mass of the WD and core match the number of SN Ia with massive CSM as deduced from observations.

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