Evolution of Magnetized White Dwarf Binaries to Type Ia Supernovae

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Abstract

With the increasing number of observed magnetic white dwarfs (WDs), the role of the magnetic field of the WD in both single and binary evolutions should attract more attention. In this study, we investigate the WD/main-sequence star binary evolution with the Modules for Experiments in Stellar Astrophysics code, by considering WDs with non-, intermediate, and high magnetic field strength. We mainly focus on how the strong magnetic field of the WD (in a polar-like system) affects the binary evolution toward Type Ia supernovae (SNe Ia). The accreted matter goes along the magnetic field lines and falls down onto polar caps, and it can be confined by the strong magnetic field of the WD, so that the enhanced isotropic pole-mass transfer rate can let the WD grow in mass even with a low mass donor with a low Roche-lobe overflow mass transfer rate. The results from the magnetic confinement model show that both the initial parameter space for SNe Ia and characteristics of the donors after SNe Ia are easily distinguishable from those found in previous SNe Ia progenitor models. The predicted nature of the donors are compatible with the non-detection of a companion in several SN remnants and nearby SNe.

Key words: binaries: general – stars: evolution – stars: magnetic field – supernovae: general – white dwarfs

1. Introduction

The evolution of a white dwarf (WD) binary to a type Ia supernova (SN Ia) has been widely studied. There are, however, still open questions concerning the WD binary evolution and origin of SNe Ia. There are two popular scenarios leading to the thermonuclear explosion of a WD as an SN Ia (Hoyle & Fowler 1960; Webbink 1979; Nomoto 1982; Iben & Tutukov 1984; Webbink 1984; Hachisu et al. 1996; Ablimit et al. 2016). One is the single degenerate (SD) model, in which a CO WD accumulates mass from a non-degenerate donor star. In the other, the so-called double degenerate model, the merger of two WDs in a binary leads to an SN Ia. Some other scenarios have also been proposed including the core-degenerate scenario in which a merger of a WD with the core of an asymptotic giant branch star or a red giant star may produce an SN Ia during the final stage of the common envelope evolution (Kashi & Soker 2011; Soker 2011). However, it is still under debate as to which scenario contributes to the observed SNe Ia (e.g., Howell 2011; Maeda & Terada 2016; Livio & Mazzali 2018).

In the SD scenario, the mass transfer and accretion (mass retention efficiency) are key issues (Kahabka & van den Heuvel 1997). To realize the steady burning and let a WD grow in mass (Nomoto et al. 2007; Shen & Bildsten 2007), the material should be transferred from a relatively massive main-sequence (MS) star or a low-mass (sub)giant star on a thermal or nuclear timescale (Rappaport et al. 1994; Hachisu et al. 1996; Yungelson et al. 1996; Li & van den Heuvel 1997; Wang et al. 2010). As a consequence, the SD model generally predicts the existence of a non-degenerate companion star at or after the SN explosion of the primary WD. However, no such companion star has yet been directly identified. For some nearby SNe and SN remnants (SNRs), upper limits on the luminosity of the companion star have been used to reject some parameter space in the SD scenario (Maoz et al. 2014; Ruiz-Lapuente 2014).

However, it is still too early to conclude that the SD scenario cannot be a major pathway toward SNe Ia. It is possible that there are some important physical processes as yet missing in modeling the evolution of mass-accreting WD binaries. Indeed, different groups have treated the mass transfer and accretion processes differently to investigate the outcome of the SD scenario, which is sensitive to the treatment (e.g., King & van Teeseling 1998; Hachisu et al. 2008; Ablimit et al. 2014). Also, observations of some supersoft X-ray sources (SSSs) are in tension with current WD binary evolution models (Ablimit et al. 2014; Ablimit & Li 2015). These suggest that there could be a missing process in the current models of accreting WD binary evolution, and this might affect the parameter space of the SD scenario toward SNe Ia.

Around 10% of the observed WDs are estimated to have magnetic field strengths from $10^{3}$ to a few $\times 10^{9}$ Gauss in volume-complete samples (Liebert et al. 2003; Schmidt et al. 2003; Kawaka et al. 2007). The role of magnetic field in the WD binary evolution has not been sufficiently explored, while it has been pointed out that the magnetic field has crucial effects on the evolution of WD binaries (e.g., Ablimit et al. 2014; Farihi et al. 2017). Cataclysmic variables (CVs) are another system of interacting WD binaries undergoing mass transfer from an MS star or brown dwarf star to the WD. Around 25% of all known CVs are magnetic (Ferrario et al. 2015). They are divided into non-magnetic CVs (<1 MG), intermediate polars (~1–10 MG) and polars (>10 MG) depending on the magnetic field strength of the WD, and the observed WD magnetic field strength so far is up to 230 MG (Schmidt et al. 1999). Magnetic WDs in SSSs and symbiotic binaries have also been discovered (Kahabka 1995; Sokoloski & Beldsttlin 1999; Osborne et al. 2001). The mean mass of highly magnetized WDs is $\sim 0.8M_{\odot}$ which is significantly higher than that of non-magnetic WDs, $\sim 0.6M_{\odot}$ (Kepler et al. 2013). This implies that the evolution and mass growth of magnetic WDs are different from those of non-magnetic WDs.

Norton et al. (2008) discussed the spin–orbit equilibrium mediated by the magnetic field for the intermediate polar system, and applied the results to CV evolution. One possible effect of the magnetic field toward SNe Ia has been recently discussed by Neunteufel et al. (2017), who examined the
helium accretion onto a weakly magnetized CO WD, taking into account the angular momentum transport by the magnetic field. They claimed that this kind of evolution could lead to fast and faint SNe Ia rather than classical SNe Ia. The effect of the strong magnetic field on the WD binary accretion process, however, is largely unexplored. For the magnetic WD binaries, Livio (1983) proposed that the accreted matter can be confined in the polar regions if the WD in the binary has sufficiently strong magnetic field strength (see also Wheeler 2012). Cumming (2002) found the Ohmic diffusion timescale of the magnetic field of the WD is much longer than the accretion timescale. Therefore, the accreted mass is expected to be confined in the polar caps.

In this paper, we first specifically address the magnetic confinement model. We investigate the possible influence of the magnetic field of the WD during the binary evolution, and present detailed numerical calculations of the mass transfer process. In Section 2, we describe our models to treat the binary evolution processes including magnetic confinement. The results are presented in Section 3. The paper closes in Section 4 with conclusions and a discussion.

2. WD Binary Evolution with Magnetic Confinement

We calculate the WD binary evolution including an MS donor star with initial masses ($M_\text{D}$) ranging from 0.8 to 8 $M_\odot$, using the version (10000) of Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2011, 2013, 2015). The initial orbital period ranges from 0.1 to 30 days. Within the parameter space, the donor mass and orbital period are discretized with bins of 0.1 $M_\odot$ and 0.2 days, respectively. The WD is approximated as a point mass. A typical Population I composition with H abundance $X = 0.70$, He abundance $Y = 0.28$, and metallicity $Z = 0.02$ is taken for the donor star. The formula used for the effective Roche-lobe (RL) radius of the donor star (Eggleton 1983) is

$$ R_{\text{L,d}} / a = \frac{0.49 q^{7/3}}{0.6q^{2/3} + \text{ln}(1 + q^{1/3})}, $$

where $q = M_\text{D}/M_{\text{WD}}$ and $a$ is the orbital separation. The Ritter scheme (Ritter 1988; Paxton et al. 2015) is adopted to calculate the mass transfer via RL overflow (RLOF) in the code. The angular momentum loss caused by gravitational wave radiation (Landau & Lifshitz 1975) and magnetic braking of the companion (Verbunt & Zwaan 1981; Rappaport et al. 1983) is also included. Other stellar and binary evolution parameters are fixed as the typical ones introduced in the MESA instrumental papers (e.g., Paxton et al. 2015).

In order to see the effect of the high magnetic field of the WD, we consider non-magnetic and magnetic WDs with initial masses ($M_{\text{WD,i}}$) of 0.8 $M_\odot$, 1.0 $M_\odot$, and 1.2 $M_\odot$. In magnetic WD binaries, the magnetic field strengths of the WDs are assumed as $B = 1.53 \times 10^9$, $1.10 \times 10^9$, and $2.00 \times 10^9$ Gauss. We assume the WD explodes as an SN Ia when it grows in mass and reaches the Chandrasekhar limit mass ($M_{\text{Ch}} = 1.38 M_\odot$). Accreting WDs may rotate differentially, and they may not reach the central carbon ignition condition even when they grow beyond the canonical Chandrasekhar limit (Yoon & Langer 2004). However, we assume all WDs explode when their mass reach the Chandrasekhar limit in order to highlight the role of the magnetic field in the SD scenario.

2.1. Magnetic Confinement during Mass Transfer

If the magnetic field is not strong enough, an accretion disk around the WD can be formed after the donor fills its RL and starts the mass loss through Lagrangian point 1. In the polar-like systems, the strong magnetic field of the WD lets the binary have a synchronous rotation and prevents accretion disk formation (Cropper 1990). The stream of matter from the donor is captured by the magnetic field of the WD, then it follows the magnetic field lines and falls down onto the magnetic poles of the WD as an accretion column (see Figure 1). Livio (1983) showed that the magnetic confinement can suppress the nova burst even at a low mass transfer rate. Livio also pointed out that the critical value of the magnetic field strength to realize magnetic confinement depends on the mass of the WD.

The appropriate physical condition for the magnetic confinement is that the magnetic field strength $B$ of the WD satisfies (Spitzer 1962; Livio 1983)

$$ B \geq 9.3 \times 10^7 \left( \frac{R_{\text{WD}}}{5 \times 10^8 \text{cm}} \right)^{7/10} \left( \frac{P_b}{5 \times 10^{10} \text{dyne cm}^{-2}} \right)^{7/10} \left( \frac{M_{\text{WD}}}{10^{-10} M_\odot \text{yr}^{-1}} \right)^{-1/2}, $$

where $M$ is the RLOF mass transfer. $P_b$ is the pressure at the base of the accreted matter. For the mass ($M_{\text{WD}}$)–radius ($R_{\text{WD}}$) relation of the WD, the following equation is used (Nauenberg 1972):

$$ R_{\text{WD}} = 7.8 \times 10^8 \left( \frac{M_{\text{WD}}}{M_{\text{Ch}}} \right)^{2/3} - \left( \frac{M_{\text{WD}}}{M_{\text{Ch}}} \right)^{2/3}, $$

where $M_{\text{Ch}}$ is the Chandrasekhar limit mass. Accreted matter will attempt to diffuse perpendicularly to the magnetic field lines and spread over the WD’s surface, and the condition...
(2) means that the diffusion timescale of the accreted matter is longer than the time required to build up the necessary pressure for an outburst (see Woosley & Wallace 1982). Stable hydrogen burning will occur instead of the outburst if the magnetic field strength of the WD fulfills condition (2).

The strong magnetic field confinement can inhibit the nova outburst, according to the following arguments by Livio (1983). The nova outburst is expected to occur if the mass of the accreted material is sufficiently large when \( P_b \) reaches to a certain critical value (a few \( 10^{10} \) dyne cm\(^{-2} \)) to initiate hydrogen burning (Fujimoto 1982a, 1982b; Livio 1983). This condition is transferred to a critical mass transfer rate, below which the nova outburst takes place (Kato et al. 2017). If the accreted matter is confined to the polar column, then the following isotropic pole-mass transfer rate \( (M_p) \) should be compared to the critical mass transfer rate, rather than the usual RLOF mass transfer rate \( (M) \). The isotropic pole-mass transfer rate \( (M_p) \) is given as

\[
M_p = \frac{S}{\Delta S} \dot{M},
\]

where \( S \) is the surface area of the WD, and \( \Delta S \) is that of the dipole regions. \( \Delta S \) can be calculated using the equations of dipole geometry and Alfvén radius of the magnetic WD. Livio (1983) showed that the isotropic pole-mass transfer rate should always become larger than the critical accretion rate, in the case where the magnetic field is so strong as to satisfy condition (2) for a pressure \( (P_b) \) not appropriate for the initiation of a nova outburst (i.e., \( \sim 5 \times 10^{10} \) dyne cm\(^{-2} \)). The highly magnetized WD can therefore grow in mass without a nova eruption (see Section 2.2).

2.2. Mass Growth of the Magnetized WD

The mass transfer rate is important to realize stable hydrogen and helium burning in the WD, and it will affect its mass retention and growth. Kato et al. (2017) summarized the possible factors that affect the mass retention efficiency and discussed the results of several groups on this efficiency. We adopt the prescription of Prialnik’s group for the efficiency of hydrogen burning (see Prialnik & Kovetz 1995; Yaron et al. 2005; Hillman et al. 2015, 2016), and adopt the methods of Kato & Hachisu (2004) for the mass accumulation efficiency of helium. The mass growth rate of the WD is

\[
\dot{M}_{WD} = \eta_H \eta_{He} \dot{M},
\]

where \( \eta_H \) and \( \eta_{He} \) are the efficiencies of hydrogen and helium burning,\(^1\) and \( \dot{M} \) is the RLOF mass transfer rate to the WD. For a WD binary with non-magnetic or weak magnetic field, the burning efficiencies are determined by the RLOF mass transfer rate (\( \dot{M} \)). For WD binaries with a strong magnetic field, \( \dot{M} \) in the prescriptions for \( \eta_H \) and \( \eta_{He} \) should be replaced by the isotropic polar-mass transfer rate (\( M_p \)). The nova eruption will take place when the RLOF mass transfer rate is lower than \( \sim 10^{-7} M_\odot \) yr\(^{-1} \) in the non-magnetic case, and this prevents WD mass growth.\(^2\) In the case of highly magnetized WD binaries, the isotropic polar-mass transfer rate can be higher than \( \sim 10^{-7} M_\odot \) yr\(^{-1} \) even with a low RLOF mass transfer rate.

For example, \( \eta_H \) is (practically) 0 when the mass transfer rate \( \dot{M} \sim 10^{-9} M_\odot \) yr\(^{-1} \) in the non-magnetic or weak magnetic field case. However, in the high magnetic field case, \( M_p > 10^{-7} M_\odot \) yr\(^{-1} \) even with a RLOF mass transfer rate \( \dot{M} \sim 10^{-9} M_\odot \) yr\(^{-1} \), and \( \eta_H \sim 1 \). Therefore, the magnetized WD can grow in mass and reach to \( M_{Ch} \) in the magnetic confinement model.

3. Results

3.1. Effect of the Magnetic Field in WD Binary Evolution

We select some examples to show the binary evolution with and without magnetic confinement under different initial conditions. Figure 2 shows a WD binary evolution (\( M_{WD,i} = 1.2 M_\odot \), \( M_{donor,i} = 1.2 M_\odot \), and initial orbital period of 10 days) without and with the magnetic field. In the non-magnetic case, the RLOF mass transfer rate in this binary is too low to let the WD grow in mass, and it evolves as a typical CV with a period gap (see Paxton et al. 2015). In the early phase before \( \log_{10} t \sim 9.78212 \), the angular momentum loss due to magnetic braking and RLOF mass transfer rate in both cases are basically the same. However, in the later evolution after \( \log_{10} t \sim 9.78212 \), the non-magnetic WD binary maintains RLOF mass transfer while the magnetic WD binary terminates its evolution due to the SN explosion under magnetic confinement. In the magnetic case, the magnetic field plays a crucial role; the enhanced polar mass transfer rate realizes stable burning even with low RLOF mass transfer, the nova burst can be avoided, and the WD efficiently accretes mass from the donor. Thus, the magnetic WD reaches \( M_{Ch} \) and explodes as an SN Ia, and there is no angular momentum loss due to the mass loss during the evolution (Figure 2). The orbital period evolves from 10 to 100 days in the non-magnetic case because the system loses further angular momentum in the later evolution due to the mass loss (the nova burst occurs with no significant accretion) (Figure 2). Because of the mass loss, the donor mass in the non-magnetic case evolves further toward a lower mass than the final donor mass at an SN Ia in the magnetic case. Thus, there is some difference in other properties (surface gravity and radius) of the donors in the late phases of the two cases (see Figure 2).

The evolution toward SNe Ia under the magnetic confinement scenario depends on the WD mass (Figures 2 and 3). The evolutions of \( M_{WD,i} = 0.8 M_\odot \) with an initial orbital period of 1 day and \( M_{WD,i} = 1.0 M_\odot \) with an initial orbital period of 1.2 days under the magnetic confinement model are shown in Figure 3. The initial donor stars’ masses are 1.2 \( M_\odot \) and 2.2 \( M_\odot \). If these less massive WDs in Figure 3 have large initial orbital periods, e.g., \( P_{orb,i} = 10 \) days for \( M_{WD,i} = 1.2 M_\odot \) as shown in Figure 2, there would be practically no mass exchange through the RLOF. In the first binary (left panels in Figure 3), the traditional thermal timescale mass transfer is not high enough for stable H burning to take place. However, the polar mass rate is enhanced up to a few \( 10^{-7} M_\odot \) yr\(^{-1} \) by magnetic confinement; thus the WD can grow in mass to \( M_{Ch} \).

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\(^1\) The C/O ashes from steady helium-burning shell may unstably ignite in a shell flash, but these carbon-burning flashes do not significantly affect the growth of the WD (Brooks et al. 2017).

\(^2\) In this paper, we investigate the condition of steady-state burning. However, we note that there would be a net accretion in the nova systems as well (Hillman et al. 2015, 2016; Henze et al. 2018).
In the binary with $M_{WD,i} = 1.0 \, M_\odot$ in Figure 3, the donor mass is much larger than the WD mass. Although the magnetic confinement also works, the mass transfer actually proceeds on a thermal timescale, as in typical supersoft X-ray binaries (e.g., Li & van den Heuvel 1997). With the higher mass donor (higher RLOF mass transfer rate), the polar mass transfer rate will be higher, and the outcomes will be accordingly different. Thus, the donor mass also plays an important role in the evolution. The orbital evolution is dominated by the mass loss during the earlier time of the RLOF mass transfer (see the right panels of Figure 3). Gravitational wave radiation dominates the orbital evolution in the late time of the evolution in both binaries. The binary with $M_{WD,i} = 0.8 \, M_\odot$ could not have confinement with the same magnetic field strength as the binary with $M_{WD,i} = 1.0 \, M_\odot$. The stronger magnetic field is required to realize the pole mass transfer for the less massive WD (condition (2) in Section 2.1).

### 3.2. Implications for SNe Ia

The initial donor mass and orbital period distributions to produce SNe Ia are given in Figure 4. In the figure, the results of $M_{WD,i} = 0.8 \, M_\odot$ with $B = 1.53 \times 10^8 \, G$, $M_{WD,i} = 1.0 \, M_\odot$ with $B = 1.1 \times 10^8 \, G$, $M_{WD,i} = 1.2 \, M_\odot$ with $B = 1.1 \times 10^8 \, G$, and the case of non-magnetic WD with $M_{WD,i} = 1.2 \, M_\odot$ are shown. The ranges of initial donor mass and orbital period are $0.8–2.2 \, M_\odot$ with $0.3–3.2$ days, $0.8–2.7 \, M_\odot$ with $0.3–4.0$ days, and $0.8–3.2 \, M_\odot$ with $0.3–25$ days, for those magnetic WDs with $M_{WD,i} = 0.8$, 1.0, and 1.2 $M_\odot$, respectively. For the non-magnetic WD with $M_{WD,i} = 1.2 \, M_\odot$, they are $2.2–3.4 \, M_\odot$ and $0.4–4.5$ days, consistent with typical values of previous works (e.g., Li & van den Heuvel 1997). As compared to the non-magnetic case and previous works, the ranges of initial orbital period and initial donor mass are larger for the high magnetic field case, because magnetic confinement leads to enhanced isotropic pole-mass transfer, and the accreted matter can burn stably with this higher pole-mass transfer even in the low-mass donor star. The upper limits of the regions in Figure 4 are based on the occurrence of a common envelope if the isotropic pole-mass transfer rate is higher than $10^{-7} \, M_\odot \, yr^{-1}$, and the lower limits are determined by the initiation of nova bursts if the polar-mass transfer is lower than $10^{-9} \, M_\odot \, yr^{-1}$. The left and right limits in Figure 4 are derived according to the mass–radius relation of zero-age MS stars and full exhaustion of the central hydrogen, respectively. It is worth noting that the initial orbital period can be up to 25 days when the initial donor mass is lower than $1.8 \, M_\odot$ (Figure 2). If a lower WD mass is coupled with a long orbital period, the system stays detached during the evolution, thus there is no mass exchange that the high magnetic field could affect.
The results from different values of magnetic field strength on $M_{WD,i} = 1.0 M_{\odot}$ are shown in the right panel of Figure 4. The WD binaries with lower magnetic field strengths (intermediate polar-like systems) have the same initial parameter space as the non-magnetic WD binaries. This is because the lower magnetic field strength is not sufficiently strong to...
M dotted and red solid lines are results from the binaries with WD binaries and the donor stars at the time of the SN explosion. If we select a binary with $M_{WD,i} = 0.8 \, M_\odot$, $M_{WD,i} = 1.0 \, M_\odot$, and $P_{orb,i} = 0.3$ day from the initial space distributions in Figure 4, the corresponding results in Figure 5 are $P_{orb,f} \sim 0.132$ day, $M_{WD,i} \sim 0.366 \, M_\odot$, $\log_{10}(\text{radius}/R_\odot) \sim -0.448$, $\log_{10}(g) \sim 4.899$, $\log_{10}(T_{eff}) \sim 3.752$, and $M_V \sim 8.99$, respectively. Combining the results of $M_{WD,i} = 0.8$ and $1.2 \, M_\odot$, the ranges of final donor mass, $\log_{10}(\text{radius}/R_\odot)$, $\log_{10}(\text{radius}/R_\odot)$, $\log_{10}(T_{eff})$ are $\sim 0.1$–1.42 $M_\odot$, $-0.77$–1.4, 1.43–5.2, and 3.5–3.83, respectively. The final orbital period distribution range from 0.07 to 61 days. The absolute magnitude of the donors ranges from $-0.42$ to 11 mag. The donor can be as dim as having 11 mag, since the less massive donor can now lead to an SN Ia. Such a faint donor is difficult to detect, and indeed is fainter than most (or all) of the current observational upper limits on the donor’s brightness for nearby SNe and SNRs (see below).

SN 1572 (Tycho’s Supernova) still remains controversial with regard to its surviving companion (e.g., Ruiz-Lapuente et al. 2004; Fuhrmann 2005; Ihara et al. 2007). From our results it might be possible that the surviving companion star could be too dim to detect. There are observational limits that the absolute magnitudes of any possible companion stars associated with SN 2011fe/PTF11kly and SN 1006 must be fainter than $M_V = 4.2$ and 4.9 mag, respectively (Li et al. 2011; Edwards et al. 2012; González-Hernández et al. 2012). Schaefer & Pagnotta (2012) claimed, using HST deep images, that the central area of SNR 0509–67.5 in the Large Magellanic Cloud is empty of point sources down to $M_V = 8.4$ mag. The aforementioned observational constraints on the possible surviving companions have a strong tension with what is expected by the traditional SD models, but those constraints can be consistent with the SD scenario once the effect of strong magnetic field is taken into account, as shown in this work.

4. Conclusions and Discussion

With a low mass transfer rate ($\lesssim 10^{-7} \, M_\odot \, \text{yr}^{-1}$), WDs barely grow to the Chandrasekhar mass limit because the most of the envelope is instantly ejected during nova outbursts. If the RLOF mass transfer rate is too high ($\gtrsim 10^{-6} \, M_\odot \, \text{yr}^{-1}$), the mass transfer becomes dynamically unstable and the system evolves into a common envelope (e.g., Iben & Livio 1993). To guarantee a proper mass transfer rate to realize stable burning, the donor mass (mass ratio $>5/6$) should be in the stable range. In the traditional SD model, MS donors with $\sim 2$–3.5 $M_\odot$ or giant donors with $>1.16 \, M_\odot$ (e.g., Li & van den Heuvel 1997; Schaefer & Pagnotta 2012) are required.

In this work, we calculate the WD and MS star binary evolution by assuming the WD has no, intermediate, or high magnetic field. We mainly focus on high magnetic field WD binary evolution using the MESA code under the magnetic confinement model (Livio 1983) to generate SNe Ia. In the case of non-magnetic and intermediate magnetic fields of the WD, the binary evolution and the initial parameter space are the same as given in previous works. In the magnetic confinement model, the transferred mass falls down onto the polar caps along magnetic lines and can be confined by the high magnetic field. Then, the density of the accreted matter increases due to this confinement, and the nova criterion must be evaluated with this isotropic pole-mass transfer rate. This rate can be sufficiently large to let the accreted hydrogen burn stably even with low-mass donor stars. We assume the timescale of the magnetic decay due to mass accretion is at least an order of the thermal timescale. Thus, the
high magnetic field of a WD could maintain its strength to confine the accreted matter (Livio 1983; Cumming 2002).

Under the magnetic confinement model, the initial parameter spaces for producing SNe Ia become larger than in previous studies without the effects of the magnetic field. In particular, the possible initial mass of donor stars extends to the lower-mass region, as such systems can realize stable burning in our scenario (Section 3.2). The final properties of donors derived in this paper are comparable with non-detection of (surviving) companion stars in nearby SNe and SNRs within currently reported upper limits. As an extreme example, our model allows a donor as dim as 11 mag in the absolute magnitude. We find that the delay time in our model ranges from \( \sim 10^8 \) to \( \sim 10^{11} \) yr. In the future, it will be interesting to further investigate the possible contribution of these kinds of WD binaries to the whole population and diversity of SNe Ia.

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