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The Evolution of the Type Ia Supernova Luminosity Function

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Abstract

Type Ia supernovae (SNe Ia) exhibit a wide diversity of peak luminosities and light curve shapes: the faintest SNe Ia are 10 times less luminous and evolve more rapidly than the brightest SNe Ia. Their differing characteristics also extend to their stellar age distributions, with fainter SNe Ia preferentially occurring in old stellar populations and vice versa. In this Letter, we quantify this SN Ia luminosity–stellar age connection using data from the Lick Observatory Supernova Search (LOSS). Our binary population synthesis calculations agree qualitatively with the observed trend in the >1 Gyr old populations probed by LOSS if the majority of SNe Ia arise from prompt detonations of sub-Chandrasekhar-mass white dwarfs (WDs) in double WD systems. Under appropriate assumptions, we show that double WD systems with less massive primaries, which yield fainter SNe Ia, interact and explode at older ages than those with more massive primaries. We find that prompt detonations in double WD systems are capable of reproducing the observed evolution of the SN Ia luminosity function, a constraint that any SN Ia progenitor scenario must confront.

Key words: binaries: close – nuclear reactions, nucleosynthesis, abundances – supernovae: general – white dwarfs

Supporting material: data behind figure

1. Introduction

Type Ia supernovae (SNe Ia) are often referred to as “standard candles.” However, their intrinsic light curves vary significantly: bright SN 1991T–like SNe Ia are 10 times more luminous and evolve more slowly than faint SN 1991bg–likes (see Taubenberger 2017 for a review). The relationship between intrinsic luminosity and light curve shape is often referred to as the Phillips (1993) relation, and it forms the basis for the use of SNe Ia as cosmological distance indicators.

Brighter and fainter SNe Ia also differ in their host-galaxy distributions: bright SNe Ia occur more often in low-mass spiral galaxies, while faint SNe Ia prefer high-mass ellipticals (Hamuy et al. 1995; Sullivan et al. 2006; Graur et al. 2017b). While the range of progenitor metallicities may account for some of the dispersion in the Phillips relation, no amount of metallicity variation can account for the entire SN Ia luminosity range for any progenitor scenario (Timmes et al. 2003; Shen et al. 2017). Thus, studies have suggested that the difference in host-galaxy distributions of SN Ia subtypes is due to the differing ages of the underlying stellar populations.

Linking stellar age to SN luminosity for Chandrasekhar-mass (M_{Ch}) explosion models has not been extensively studied (for one example, see Wang et al. 2014) and appears difficult, if not impossible, to achieve. Adjusting various quantities (e.g., the density at which the deflagration transitions to a detonation or the number of initial deflagration kernels) does not produce the relatively tight correlation of the Phillips relation and also fails to yield the low-luminosity, rapidly evolving SN 1991bg–likes (Sim et al. 2013; Blondin et al. 2017; although see Höflich et al. 2017). Since M_{Ch} explosions do not reproduce the full range of the Phillips relation, connecting the stellar age to the

various SN Ia subtypes is as yet impossible within the M_{Ch} paradigm. Furthermore, it is not obvious why the deflagration-to-detonation transition density or number of ignition kernels would change with age. Note that the category of M_{Ch} explosion models includes both standard “single degenerate” scenarios (e.g., Whelan & Iben 1973) as well as “double degenerate” scenarios (e.g., Webbink 1984) for which the ignition occurs at the center of a super- M_{Ch} merger remnant, as these have the same explosion mechanism and similar radiative output.

At first glance, prospects appear better for sub- M_{Ch} explosion models, in which the luminosity of the SN Ia is directly related to the mass of the exploding white dwarf (WD; Sim et al. 2010; Blondin et al. 2017; Shen et al. 2017), a quantity that could conceivably vary with stellar age. Naïvely, it seems obvious that the masses of exploding sub- M_{Ch} WDs decrease with age because WD masses are directly related to main-sequence masses, which are directly related to main-sequence lifetimes, and thus dimmer SNe Ia would occur in older stellar populations as observed.

However, half of all SNe Ia occur >1 Gyr after their progenitor systems form (e.g., Maoz et al. 2014 and references therein), much longer than the main-sequence lifetimes of the stars that produce the $\gtrsim 0.85 M_{\odot}$ WDs that yield SNe Ia. For sub- M_{Ch} explosions produced by double WD binaries, either by double detonations (Guillochon et al. 2010) or direct carbon ignitions (Pakmor et al. 2010), the age of the system at the time of interaction is instead dominated by the gravitational-wave inspiral timescale, which is itself a complicated outcome of multiple phases of stable and unstable mass transfer prior to the formation of the double WD system. Note that sub- M_{Ch} double detonation explosions may also occur in single-degenerate systems in which the donor is a non-degenerate helium-rich star (e.g., Woosley et al. 1986) or in triple star systems (Kushnir et al. 2013); however, because predicted rates from these

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systems are much lower than the SN Ia rate (Geier et al. 2013; Toonen et al. 2017b), we restrict ourselves throughout the rest of this work to sub- M_{Ch} explosions in isolated double WD systems.

In this Letter, for the first time, we quantify the evolution of exploding WD masses and resulting SN Ia subtypes for sub- M_{Ch} double WD progenitors and compare to observational constraints.⁶ In Section 2, we describe our basis for comparison: SN Ia subtypes and stellar age distributions inferred from the Lick Observatory Supernova Search (LOSS) survey. In Section 3, we detail the methodology by which we derive the theoretical SN Ia subtype evolution from the SeBa binary population synthesis code. We conclude and outline future work in Section 4.

2. Observed Evolution of the Luminosity Function

During its first decade of operations, LOSS discovered more than 1000 SNe in the 14,882 galaxies it surveyed (e.g., Leaman et al. 2011; Li et al. 2011). Li et al. (2011) constructed a volume-limited subsample that included 180 SNe and SN impostors. All SNe were classified spectroscopically, and individual SN light curves were used to calculate completeness corrections. The resulting sample is complete for SNe Ia out to 80 Mpc. The SNe in this volume-limited sample were recently reclassified, based on additional data and an updated understanding of SN physics, but SNe Ia were unaffected (Graur et al. 2017a, 2017b; Shivvers et al. 2017).

The LOSS volume-limited sample is homogeneous, well-characterized, and spectroscopically complete. However, LOSS targeted massive, luminous galaxies, so that low-luminosity galaxies and SN 1991T-like SNe Ia, which are known to preferentially occur in these galaxies, are underrepresented. With this in mind, we restrict our comparisons to the galactic ages >1 Gyr that are well sampled in LOSS. Future work will use data from volume-limited samples that include more SNe Ia in low-luminosity galaxies, which will allow us to better probe the early evolution of the luminosity function.

Of the 74 SNe Ia in the updated volume-limited sample, we use the 70 SNe Ia that were classified as “normal,” SN 1991bg-like, SN 1991T-like, or SN 1999aa-like. We exclude SNe 1999bh, 2002es, 2005cc, and 2005hk, which were classified as either SN 2002es-like or SN 2002cx-like.

Instead of relying on the discrete spectroscopic classifications of the SNe, we use the continuous and extinction-independent scale afforded by the $\Delta m_{15}(B)$ parameter, which measures the decrease in B -band magnitudes between peak and 15 d after peak. Through the Phillips (1993) width-luminosity relation, this parameter is a good proxy for the intrinsic luminosity of a SN Ia. Fifty-four SNe have $\Delta m_{15}(B)$ measurements performed by different groups (Hicken et al. 2009; Contreras et al. 2010; Ganeshalingam et al. 2013). Twenty-six SNe did not have enough points on their light curves to fit for $\Delta m_{15}(B)$ (J. M. Silverman and W. Zhang 2017, private communication). To fill in these missing values, we perform a linear fit between the extant $\Delta m_{15}(B)$ values and the light curve template number assigned to each LOSS SN by Li et al. (2011).

Next, we estimate the ages of the SN host galaxies by making use of the correlation between a galaxy’s age and its

stellar mass (e.g., Gallazzi et al. 2008). We acknowledge that this relationship has large variance and that, furthermore, the average galaxy age is at best a rough proxy for the SN Ia progenitor’s age. We leave a more accurate derivation of SN Ia progenitor age to future work.

LOSS estimated host-galaxy stellar masses based on their B - and K -band luminosities (Leaman et al. 2011), but four of our host galaxies lack such estimates; they are assigned stellar masses using the method outlined by Graur et al. (2017b). These masses are then used to estimate stellar ages using Sloan Digital Sky Survey (SDSS) data (York et al. 2000; Gallazzi et al. 2008 and private communication; Calura et al. 2014).

We can further refine our stellar age estimates by also using the morphological information of the galaxies. González Delgado et al. (2015) present luminosity-weighted ages for a range of galaxy masses and Hubble types using data from the Calar Alto Legacy Integral Field Area (CALIFA) survey. We interpolate among their results and apply a constant +0.35 dex correction to convert from luminosity- to mass-weighted ages (Goddard et al. 2017), which are more appropriate for the >1 Gyr progenitors we consider. In the following section, we compare theoretical cumulative distribution functions (CDFs) of SN Ia luminosities to observed CDFs for binned ages inferred from both methods.

3. Theoretical Evolution of the Luminosity Function

In order to predict the evolution of SN Ia subtypes from binary population synthesis calculations, we must construct a mapping from exploding WD mass, M_1 , to $\Delta m_{15}(B)$, our observational proxy. Radiative transfer simulations of a suite of sub- M_{Ch} explosions were first performed by Sim et al. (2010). Recently, Shen et al. (2017, hereafter S17) reexamined the subject using more precise detonation calculations and found significant differences in the nucleosynthetic products. In a complementary work, Blondin et al. (2017, hereafter B17) used a simplified nuclear network but improved upon the radiative transfer by employing a non-local thermodynamic equilibrium (non-LTE) code; they also found significant differences compared to Sim et al. (2010).

None of the aforementioned studies was able to completely reproduce the Phillips relation: Sim et al. (2010) and S17 derived light curves confined to high values of $\Delta m_{15}(B)$, and while B17 found a good match to the Phillips relation in the high luminosity, low $\Delta m_{15}(B)$ regime, they were unable to achieve the high values of $\Delta m_{15}(B)$ at faint luminosities. However, there are good reasons to believe that a combination of S17’s nucleosynthesis and a non-LTE radiative transfer calculation like B17’s will reproduce the Phillips relation. S17’s more detailed nucleosynthesis does not differ too substantially from that of B17 for higher WD masses $\simeq 1.1 M_{\odot}$, so a combination of the two improvements will not significantly alter B17’s good agreement with observations of bright SNe Ia. At lower WD masses $\leq 0.9 M_{\odot}$, S17’s nucleosynthesis produces ~ 3 times more ^{56}Ni than B17’s. Thus, a similar amount of ^{56}Ni is produced in an explosion with a smaller ejecta mass, which implies a more rapid light curve evolution and higher values of $\Delta m_{15}(B)$ at low luminosities, pushing B17’s non-LTE calculations in the right direction.

Confirmation of the ability of sub- M_{Ch} explosions to reproduce the entirety of the Phillips relation awaits future calculations combining detailed nucleosynthesis with non-LTE

⁶ We note that Ruiter et al. (2013) and Piro et al. (2014) also studied the SN Ia luminosity function but did not analyze its evolution with time.

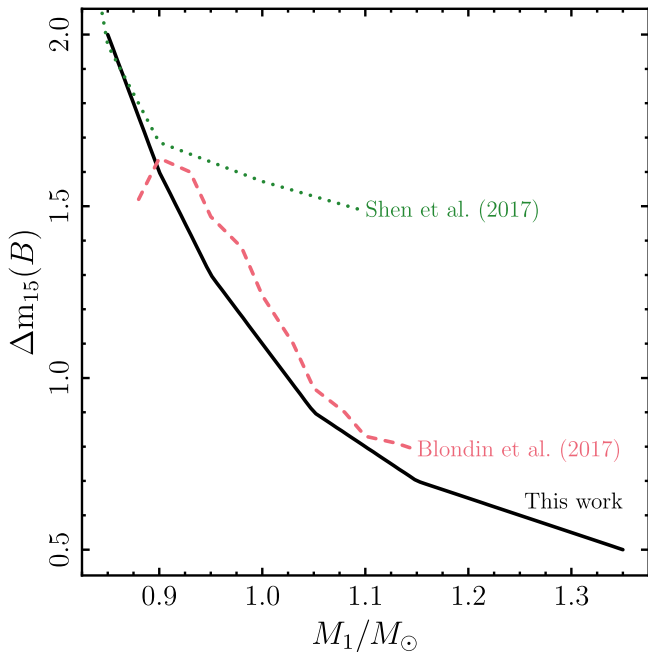


Figure 1. Assumed mapping of M_1 to $\Delta m_{15}(B)$ (solid line). A combination of the results from Shen et al. (2017; dotted line) and Blondin et al. (2017; dashed line) is used to infer the mapping.

radiative transfer. For the remainder of this work, we assume that this effort will be successful and construct an appropriate mapping of exploding WD mass to $\Delta m_{15}(B)$. We assume SN 1991bg–likes with $\Delta m_{15}(B) = 2.0$ mag are produced by the explosions of $0.85 M_{\odot}$ WDs, as found by S17. At the opposite end, we adjust B17’s results to account for the slightly boosted ^{56}Ni production found by S17, so that $1.15 M_{\odot}$ explosions yield light curves with $\Delta m_{15}(B) = 0.7$ mag. Above $1.15 M_{\odot}$, we extend the mapping with an ad hoc linear relation between WD mass and $\Delta m_{15}(B)$. Finally, in between 0.85 and $1.15 M_{\odot}$, we roughly convolve B17’s non-LTE radiation transport results with S17’s nucleosynthesis. This leads to the mapping shown in Figure 1.

We now turn to a theoretical prediction for the evolution of the exploding WD mass using the SeBa binary population synthesis code (Portegies Zwart & Verbunt 1996; Toonen et al. 2012). We employ SeBa to simulate a large number of binaries focusing on those that lead to a merger between two WDs. The simulations include stellar evolution and interactions such as mass transfer and accretion, angular momentum loss, and gravitational-wave emission.

We only consider double WD progenitors that explode promptly as sub- M_{Ch} detonations, before they can evolve into super- M_{Ch} remnants. We are agnostic as to the exact explosion mechanism, as long as it occurs shortly after the onset of mass transfer and in such a way that the light curve of the SN Ia is primarily determined by M_1 , the mass of the more massive WD, which we constrain to be a C/O WD. Explosion mechanisms that fit these criteria can occur in merging double WD systems via “dynamically driven double degenerate double detonations” (Guillochon et al. 2010) or direct carbon ignitions (Pakmor et al. 2010). Stably mass-transferring double WD systems may also lead to double detonation SNe Ia (Bildsten et al. 2007), but recent work suggests that even extreme mass ratio double WD systems will merge unstably (Shen 2015;

Brown et al. 2016), so we continue under this assumption for simplicity.

The SeBa simulations used here are based on the primary $\alpha\gamma$ -Abt model in Toonen et al. (2017a). In this model, the common-envelope (CE) prescription is tuned to best reproduce the observed double WD population (Nelemans et al. 2000; Toonen et al. 2012). The γ -CE prescription (Nelemans et al. 2000) is applied with $\gamma = 1.75$, unless the binary contains a compact object or the CE is triggered by a tidal instability. In the latter case, the classical α -CE prescription is applied (Paczynski 1976; Webbink 1984) with $\alpha\lambda = 2$. The initial orbital separations follow a power-law distribution with an exponent of -1 (Abt 1983). For further information, see Toonen et al. (2017a and references therein). Note that while we show results using the γ -formalism in this Letter, the trends remain if we exclusively use the α -prescription with $\alpha\lambda = 2$.

The retention efficiency of helium has been updated with respect to Toonen et al. (2017a). Based on recent modeling of helium accretion onto WDs (Piersanti et al. 2014; Brooks et al. 2016), we assume that WDs accrete helium conservatively when the logarithm of the mass transfer rate is between

$$\log_{10}\left(\frac{\dot{M}_{\text{upper}}}{M_{\odot}/\text{yr}}\right) = -7.226 + 2.504\left(\frac{M_{\text{WD}}}{M_{\odot}}\right) - 0.805\left(\frac{M_{\text{WD}}}{M_{\odot}}\right)^2 \quad (1)$$

and

$$\log_{10}\left(\frac{\dot{M}_{\text{lower}}}{M_{\odot}/\text{yr}}\right) = -8.918 + 4.099\left(\frac{M_{\text{WD}}}{M_{\odot}}\right) - 1.232\left(\frac{M_{\text{WD}}}{M_{\odot}}\right)^2, \quad (2)$$

where M_{WD} is the mass of the accreting WD. Outside of this regime, the accretion is assumed to be completely non-conservative. The updated helium retention efficiency leads to less WD mass growth compared to previous assumptions (Kato & Hachisu 1999; Bours et al. 2013; Ruitter et al. 2013).

Figure 2 shows the primary and secondary WD masses at the time of merger for short and long delay times. It is clear that there is an overabundance of $\sim 0.875 M_{\odot} + 0.825 M_{\odot}$ mergers in the old population compared to the young population. These primary masses are what we assume lead to SN 1991bg–like SNe; thus, if the currently theoretically uncertain criterion for which mergers lead to subluminous SNe includes only these binaries with relatively massive secondaries, the theoretical $\Delta m_{15}(B)$ distribution will shift toward subluminous SNe in older populations.

So as to maximize SN 1991bg–likes in old populations while including as many SN Ia overall as possible, we impose a quadratic minimum secondary mass as shown by the solid line in Figure 2. While ad hoc, there is a physical basis for our chosen criterion. More massive secondaries yield more directly impacting accretion streams, and more massive primaries have higher gravitational potentials. Both of these effects lead to higher-temperature hotspots during the merger, which more easily initiate detonations, suggesting a minimum secondary mass that varies inversely with primary mass. We note that the often-used $M_1 + M_2 > M_{\text{Ch}}$ constraint does not reproduce the observed luminosity function evolution; such a constraint

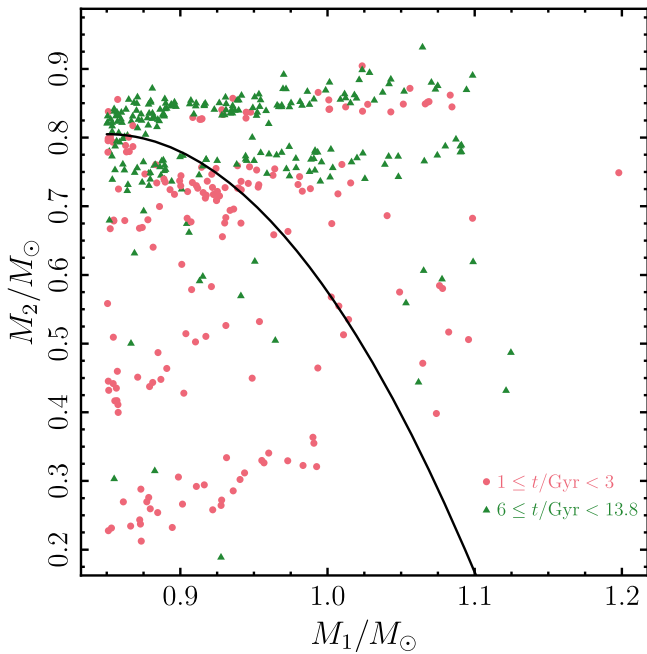


Figure 2. Primary and secondary WD masses at merger for short (1–3 Gyr; red circles) and long (6–14 Gyr; green triangles) delay times. We assume binaries above the solid line explode as SNe Ia.

yields too many subluminous SNe Ia in young stellar populations.

In order to understand the relative overproduction of WD binaries with masses $\sim 0.875 M_{\odot} + 0.825 M_{\odot}$ in the older population, we consider the evolution of main-sequence binaries with masses $5.5 M_{\odot} + 3.5 M_{\odot}$, which are the main progenitors of these double WD systems. Figure 3 shows the time between the birth of a $5.5 M_{\odot} + 3.5 M_{\odot}$ binary and the merger of its two components versus initial separation. For initial separations $< 19 R_{\odot}$, the secondary star fills its Roche lobe as it crosses the Hertzsprung gap before the primary becomes a WD, resulting in a helium star–sub-giant merger. For wider initial separations, this mass transfer occurs later, when the primary is already a WD, and leads to a CE and a surviving double WD binary whose separation and gravitational inspiral time are correlated with the initial separation. Such systems with merger times of 1–3 Gyr do exist and will lead to subluminous SNe Ia in young populations, but they are significantly outnumbered by those with merger times of 6–14 Gyr; thus, we find more faint SNe in old stellar populations.

The resulting theoretical CDFs for four age bins are shown in Figure 4. The CDFs are significantly different from one another and in qualitative agreement with the observed CDFs from LOSS: younger stellar populations host fewer dim SNe Ia than older populations. Quantitative discrepancies certainly exist between the theoretical and observed CDFs. However, given the approximations in our analysis, our goal in this Letter is to merely demonstrate that double WD mergers have the capability to explain the evolution of the SN Ia luminosity function. Note that the lack of young, low-luminosity galaxies in the LOSS sample precludes a comparison to the theoretical CDF of the youngest age bin.

The overall SN Ia rates from our binary population synthesis calculations range from $10.0 \times 10^{-15} M_{\odot}^{-1} \text{ yr}^{-1}$ 1–3 Gyr after birth to $7.3 \times 10^{-15} M_{\odot}^{-1} \text{ yr}^{-1}$ 6–14 Gyr after birth. These

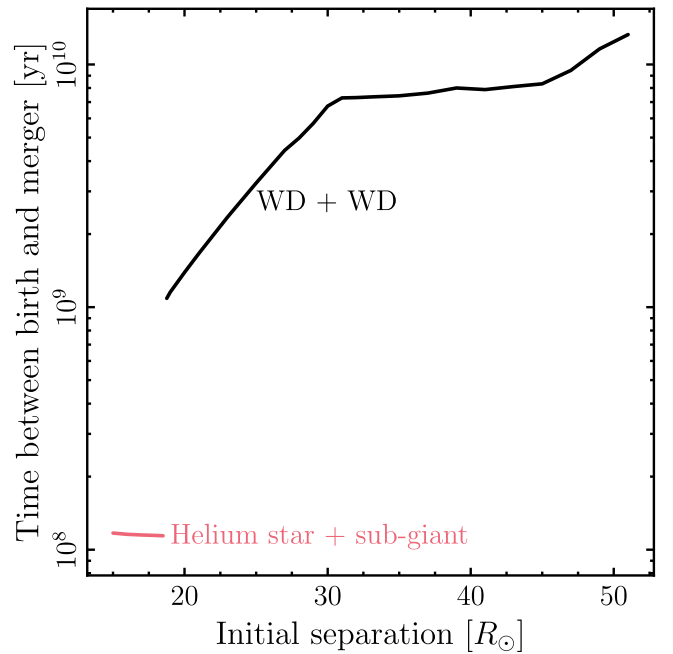


Figure 3. Time between birth and merger vs. initial separation for $5.5 M_{\odot} + 3.5 M_{\odot}$ binaries. Separations that lead to helium star–sub-giant mergers are shown in red; separations that yield double WD mergers are shown in black.

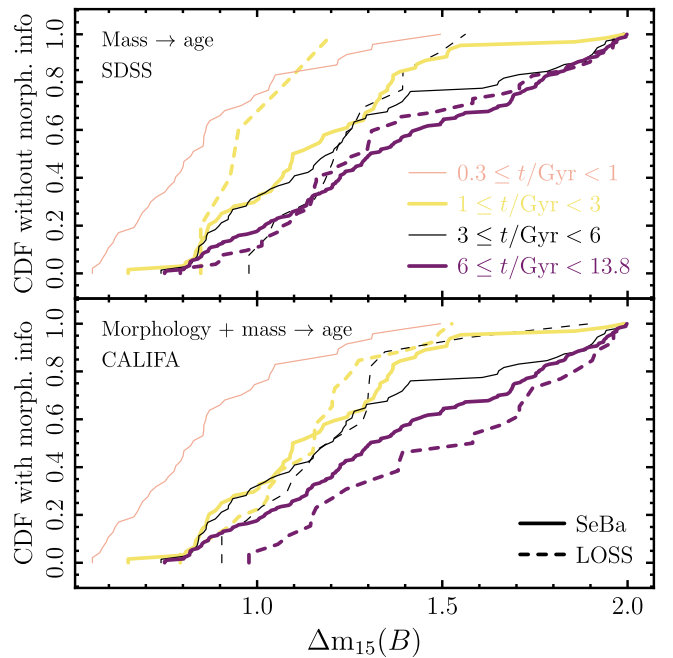


Figure 4. Cumulative distribution functions of $\Delta m_{15}(B)$ from the LOSS data (dashed lines; Section 2) for different age bins as labeled, compared to SeBa CDFs (solid lines; Section 3). The LOSS CDFs in the top panel use relations derived from SDSS data to estimate ages from galaxy masses; stellar ages in the bottom panel are inferred from galaxy masses and morphologies using data from the CALIFA survey. The youngest age bin’s theoretical CDF does not have an observational counterpart. (The data used to create this figure are available.)

rates are 3–10 times lower than the observed delay time distribution (Maoz & Graur 2017). However, this disagreement is within current uncertainties given the similar factor of a few discrepancy between the observed and theoretical local

double WD space densities (Maoz & Hallakoun 2017; Toonen et al. 2017a).

4. Conclusions

In this Letter, we have shown that prompt detonations in double WD systems can qualitatively explain the time evolution of the SN Ia luminosity function. Given the many approximations we have made, precise agreement between theory and observations is not expected and indeed is not achieved; we simply demonstrate a proof of concept.

The largest observational uncertainties relate to our derivation of stellar ages from global galaxy properties such as mass and morphology. Future work can improve these age estimates by including information, particularly star formation proxies, local to the SN Ia site. Furthermore, upcoming surveys such as the Zwicky Transient Facility and the Large Synoptic Survey Telescope will greatly increase the numbers of SNe Ia, reducing Poisson errors and allowing more finely grained age bins, particularly for the low-mass, young galaxies not probed by LOSS.

The theoretical side of this work relies on several assumptions that will be improved in the near future. A combination of more precise detonation simulations and non-LTE radiative transfer calculations is currently underway and will better quantify the mapping between exploding WD mass and $\Delta m_{15}(B)$. Future merger simulations will determine the minimum secondary mass that can trigger the primary WD to explode, obviating the need to impose an ad hoc constraint. Furthermore, concrete progress is being made in modeling CEs, which will reduce one of the largest binary population synthesis uncertainties.

A more quantitative study measuring and reproducing the evolution of the SN Ia luminosity function awaits these and other improvements. Our work in this Letter simply demonstrates that prompt detonations in double WD systems have the capacity to match this evolution, a constraint that any progenitor scenario attempting to explain the majority of SNe Ia must confront.

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