THE PROGENITORS OF TYPE Ia SUPERNOVAE. II. ARE THEY DOUBLE-DEGENERATE BINARIES? THE SYMBIOTIC CHANNEL

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ABSTRACT

In order for a white dwarf (WD) to achieve the Chandrasekhar mass, \( M_C \), and explode as a Type Ia supernova (SNIa), it must interact with another star, either accreting matter from or merging with it. The failure to identify the class or classes of binaries which produce SNIa is the long-standing “progenitor problem.” Its solution is required if we are to utilize the full potential of SNIa to elucidate basic cosmological and physical principles. In single-degenerate models, a WD accretes and burns matter at high rates. Nuclear-burning white dwarfs (NBWDs) with mass close to \( M_C \) are hot and luminous, potentially detectable as supersoft X-ray sources (SSSs). In previous work, we showed that >90%–99% of the required number of progenitors do not appear as SSSs during most of the crucial phase of mass increase. The obvious implication might be that double-degenerate binaries form the main class of progenitors. We show in this paper, however, that many binaries that later become double degenerates must pass through a long-lived NBWD phase during which they are potentially detectable as SSSs. The paucity of SSSs is therefore not a strong argument in favor of double-degenerate models. Those NBWDs that are the progenitors of double-degenerate binaries are likely to appear as symbiotic binaries for intervals \( >10^5 \) years. In fact, symbiotic pre-double-degenerates should be common, whether or not the WDs eventually produce SNIa. The key to solving the Type Ia progenitor problem lies in understanding the appearance of NBWDs. Most of them do not appear as SSSs most of the time. We therefore consider the evolution of NBWDs to address the question of what their appearance may be and how we can hope to detect them.

Key words: binaries: symbiotic – distance scale – supernovae: general – white dwarfs – X-rays: general

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1. INTRODUCTION

Type Ia supernovae (SNIa) have been used to map the expansion history of the universe. The results have been exciting, indicating epochs of deceleration and acceleration, and suggesting the presence of dark energy (see, e.g., Riess et al. 2007; Kuznetsova et al. 2008). Unfortunately, we have not yet identified the astronomical systems that produce these distinctive explosions. (See Kotak 2008 and Branch et al. 1995 for reviews.) Until we do, it will be impossible to understand or quantify the systematic uncertainties and to optimize the further use of SNIa to explore physics and cosmology. The SNIa progenitor problem is therefore considered to be one of the key outstanding questions in astronomy today.

We know that the explosions occur when a white dwarf (WD) gains mass from a binary companion. Indications from both theory and observation are that the supernova is triggered when the WD reaches the Chandrasekhar mass, \( M_C \) (Mazzali et al. 2007). What we do not know are the characteristics of the binary. Is the donor on the main sequence evolved, or degenerate? Whatever the nature of the donor, it must be able to contribute enough mass to the WD to allow it to transition from its starting mass to \( M_C \).

In single-degenerate binaries, the rate of mass transfer to a WD from a non-degenerate donor must be high enough that matter can be burned in either a quasisteady way or else during recurrent novae, thereby eliminating opportunities for more explosive nuclear burning that can reduce the mass of the WD (Iben 1982; Nomoto 1982; Fujimoto 1982). That is, the WDs that reach \( M_C \) must process accreting matter; they are nuclear-burning white dwarfs (NBWDs) for long intervals. They are therefore potentially detectable as hot, luminous supersoft X-ray sources (SSSs) during the crucial epoch when the WD’s mass is increasing. \(^1\) Some bright SSSs may be progenitors of SNIa (Rappaport et al. 1994; Di Stefano & Rappaport 1994). Nevertheless, the companion paper (Di Stefano 2010; see also Di Stefano et al. 2010 and Di Stefano 2007) shows conclusively that the majority of the progenitors do not appear as bright SSSs during intervals long enough (\( \sim 10^5 \) yr) to allow quasisteady burning of the necessary amounts of accreting matter. For both spiral and elliptical galaxies, the discrepancy is at least an order of magnitude, perhaps as much as 2 orders of magnitude. In addition, we found that existing data already place restrictions on sub-Chandrasekhar models. These restrictions may be tightened as additional exposures with Chandra and XMM-Newton are taken and more data are analyzed.

The most obvious interpretation of the mismatch is that it rules out single-degenerate models. In fact, a weaker measure of the mismatch was recently derived for six early-type populations, and was used to argue that single degenerates can produce not more than 5% of the SNIa in early-type galaxies (Gilfanov & Bogdán 2010). If single degenerates are ruled out, then the alternative would appear to be double-degenerate models in which two carbon–oxygen (C–O) WDs execute a close orbit. In order for the WDs to come to interact in a Hubble time, they must have had an opportunity to spiral toward each other in a common envelope. This paper explores the epoch prior to the common envelope. In Section 2, we find that, immediately before the common envelope phase that produces a close double degenerates, an epoch of nuclear burning on an accreting WD is

\(^1\) The known SSSs typically have 30 eV \(< kT < 100 \) eV and \( 10^{-8} \) erg s\(^{-1} \) \(< L_X < 10^{38} \) erg s\(^{-1} \). NBWDs with mass near \( M_C \) have surface temperatures and luminosities at the top end of these ranges. (See Figure 1 of the companion paper (Di Stefano 2010).)
expected. In Section 3, we predict the numbers of NBWDs required if the double-degenerate channel is the main route to SNeIa. We then compare these numbers with the numbers of SSSs detected in external galaxies, and find a large mismatch. In Section 4, we discuss the significance and implications of the mismatch. Section 5 focuses on the symbiotic nature of pre-double-degenerate binaries and discusses the prospects for using the distinctive symbiotic phase to test double-degenerate models for SNIa progenitors. Our conclusions are presented in Section 6.

The bottom line is that, for neither young nor old populations can the absence of SSSs be interpreted as evidence for the absence of NBWDs. If the photospheres of NBWDs are large, soft X-rays may not be emitted. In fact, photospheric adjustments in known SSSs seem to occur (see, e.g., Greiner & Di Stefano 2002). In addition, local mass associated with the system, such as winds, can absorb radiation from the WD. In fact, the very binaries most likely to produce SNeIa must eject significant winds if they are to survive (Di Stefano et al. 1997; Di Stefano & Nelson 1996; Di Stefano 1996).

2. DOUBLE DEGENERATES AND NUCLEAR BURNING

2.1. Overview

In order for two WDs to come close enough to each other to either exchange mass or merge in a Hubble time, they must be separated by a distance no larger than a few $R_\odot$. This requires a prior common envelope phase, initiated when a giant with a well-formed core fills its Roche lobe, typically at a point when it is more massive than its WD companion.

Below we consider binaries about to enter a common envelope phase and emerge as double degenerates with total mass greater than the Chandrasekhar mass. Even before describing the calculations, however, we can explain why, prior to the common envelope, the WD is likely to burn some of the matter impinging on it. This is because the rate of mass infall, $M_{\text{in}}$, produced by winds from a giant, is comparable to what is needed for quasi-steady nuclear burning. Most of the mass lost by a giant is winds, which can absorb radiation from the WD. In fact, the very binaries most likely to produce SNeIa must eject significant winds if they are to survive (Di Stefano & Nelson 1996; Di Stefano 1996).

Consider a binary in which neither star is massive enough to produce a core-collapse supernova, and in which the star that was initially the most massive, star “1,” has already evolved. Let $M_{1,\text{wd}}$ represent the mass of the first-formed WD, $M_{2,\text{ce}}$ represent the total mass of the giant just at the point when it fills its Roche lobe, and $M_{2,\text{wd}}$ the mass of its core at the same time. We consider as potential progenitors of SNeIa those binaries in which the WDs are C-O WDs, with $M_{1,\text{wd}} + M_{2,\text{wd}} > M_C$. We use a uniform distribution to select the value of $M_{1,\text{wd}}$ to lie in the range $0.55 M_\odot$–$1.35 M_\odot$, and then the value of $M_{2,\text{wd}}$ to lie in the range $0.45 M_\odot$–$M_{1,\text{wd}}$.

The following situation triggers a common envelope: when star “2” fills its Roche lobe, the effect of mass transfer is to further shrink the Roche lobe, while the star itself is unable to shrink. In order for this to occur, $M_{2,\text{ce}} > \eta M_{1,\text{wd}}$. Typically, $\eta > 1$. The value of $\eta$ for each individual system depends on the amount of mass ejected from the system, the angular momentum carried by ejected mass, and the mass ratio. Keeping the stability criterion in mind, we select the values of $M_{2,\text{ce}}$ from a uniform distribution: $M_{1,\text{wd}} < M_{2,\text{ce}} < 7.6 M_\odot$. The upper limit was chosen to allow for the fact that the initial mass of the secondary, $M_2$, is larger than $M_{2,\text{ce}}$. In addition, the initial mass of the primary is larger than $M_2$. We took the upper limit on $M_1$ to be $8 M_\odot$, roughly corresponding to the most massive star that becomes a WD.

Prior to filling its Roche lobe, star “2” was emitting a wind. We have modeled the wind using a Reimer’s-type law, modified so that it satisfies the following conditions. First, although there may be modest mass loss during the main-sequence and subgiant phase, significant mass loss starts only when the core mass reaches a critical value $c_0$. The Reimer’s form then ensures that $M_{\text{wind}}$ increases with time, more dramatically as the core mass reaches its final value. The second condition we impose is that, for stars evolving in isolation, the integrated mass lost through winds is $M_2 - M_{2,\text{wd},0}$, where $M_{2,\text{wd},0}$ is the mass a star of initial
mass $M_2$ would produce, were it to evolve in isolation. The values of $M_{2 \mathrm{wd}}$ and $M_2$ are related to each other through an initial-mass-final-mass relationship: $M_f = 0.123 M_n + 0.358$. (See Kalirai et al. 2008; Catalán et al. 2009; Dobbie et al. 2006; Williams 2007; Weidemann & Koester 1983.) We assume that, prior to the point at which the donor filled its Roche lobe, the decrease in the giant’s mass can be modeled with the analytic form derived by integrating over the mass lost through winds.

When the giant has a companion, a fraction of the mass it loses comes under the gravitational influence of the companion. The geometry of the binary and the winds, and the wind speed, determine how much mass can be captured by the companion. When the giant is close enough to its companion that it is about to fill its Roche lobe, the winds are partially focused. We use the expression

$$M_{\text{in}} = \frac{1}{4} M_{\text{winds}} \left( \frac{R_{2}(t)}{R_{\text{RL}}(t)} \right)$$

$M_{\text{in}}$ represents the rate of mass infall to the WD, and $R_2(t)$ and $R_{\text{RL}}(t)$ are the instantaneous values of the physical radius and Roche lobe radius of star “2.”

In the top panel of Figure 1, $\dot{M}_{\text{in}}$ versus $M_{1, \text{wd}}$ is shown for systems in which the giant is about to fill its Roche lobe. Green (red) points correspond to binaries in which the combined WD masses sum to more (less) than $M_C$. Plotted as black curves are $M_{\text{min}}$ and $M_{\text{max}}$ as a function of the accretor mass. These are, respectively, the minimum value of $M_{\text{in}}$ for which quasi-steady nuclear burning can occur and the maximum value of $M_{\text{in}}$ for which all of the incoming mass can be burned as it accretes.

The striking feature of this plot is that, for many systems, the rate of mass infall at the time of Roche lobe filling is in or near the steady-burning regime. Furthermore, this would be the case under a wide range of assumptions about the infall rate. That is, many points on this plot would fall within or straddle the steady-burning regime even if a larger or smaller fraction of the giant’s winds were captured by the WD, or even if the winds were emitted by star “2” at a somewhat higher or lower rate, or even if the values of $M_{\text{min}}$ and $M_{\text{max}}$ were to differ somewhat from those shown in the figure. It is therefore a robust result that, just before the common envelope phase, mass is infalling on many of the first-formed WDs at rates compatible with quasi-steady nuclear burning.

We next evolve each binary represented in the top panel of Figure 1 backward in time, until the point at which the giant’s core mass is $c_0$. To compute the evolution, we must model the fraction $\beta$ of infalling mass that can be retained by the WD. The value of $\beta$ depends on how the rate of infall compares with the minimum and maximum rates compatible with steady nuclear burning, $M_{\text{min}}$ and $M_{\text{max}}$. For $M_{\text{in}} < 1/3 M_{\text{min}}$, we assume that no mass is retained. For rates of infall between $1/3 M_{\text{min}}$ and $M_{\text{min}}$, we take $\beta = 0.4$. In the steady-burning regime, we use $\beta = 0.8$. For $M_{\text{in}} > M_{\text{max}}$, we use $\beta = 0.8 M_{\text{max}} / M_{\text{in}}$. With this prescription, we can compute the initial mass $M_{1, \text{wd}}(0)$ of the first-formed WD, and compare it with the mass $M_{1, \text{wd}}(f)$ at the time star “2” fills its Roche lobe.

The results are shown in the bottom panel of Figure 1. For the systems in our simulation, more than 0.05 $M_\odot$ (0.15 $M_\odot$) was gained by 50% (37%) of the WDs in binaries that would eventually go on to become double degenerates with $M_{\text{tot}} > M_C$. The distributions of properties among the binaries in our simulation are unlikely to mirror the distributions found in nature. Nevertheless, our results show that mass gain by the first-formed WDs in double-degenerate binaries may be common and can often be significant. This has a potentially important implication for the rate of SNeIa that could be produced by double-degenerate binaries, since mass gain by the first-formed WD can increase the numbers of double-degenerate binaries in which the total WD mass exceeds $M_C$.

For the work in this paper, we focus on the connection between nuclear burning and detectability. Since nuclear burning is common among pre-double-degenrate, these binaries must be bright and are therefore potentially detectable during an extended interval just prior to the common envelope. Near the surface of the WD nuclear burning produces temperatures and luminosities characteristic of SSSs.

The pre-double-degenerate in which the total WD mass will exceed $M_C$ are not the most common pre-double-degenerate. It is therefore important to also consider those binaries for which the total white dwarf mass is smaller than $M_C$. These are shown as the red points in the bottom panel of Figure 1. While these binaries are presumably not good candidates for SNeIa progenitors, they too can experience long epochs during which nuclear burning and SSS-like behavior occur. In these systems, the first-formed WDs tend to gain less mass. In our simulation, only 18% gain more than 0.05 $M_\odot$, 5% gain more than 0.12 $M_\odot$, and 2% gain more than 0.15%. Nevertheless, because more such binaries are expected, they can comprise a significant component of bright NBWDs that have the potential to be detected as SSSs.

3. NUMBER OF NUCLEAR-BURNING PRE-DUOUBLE-DEGENERATES

3.1. Predictions

We have found that, prior to the common envelope producing the double degenerate, there is a time interval, $\tau_{\text{acc}}$, during which the values of $M_{\text{in}}$ are compatible with quasi-steady nuclear burning and mass retention. Let $\Delta M$ represent the mass gained during this interval.

$$\frac{\Delta M}{0.1 M_\odot} = \left( \frac{\tau_{\text{acc}}}{1 \times 10^6 \text{ yr}} \right) \left( \frac{\beta M_{\text{in}}}{1 \times 10^{-7} M_\odot \text{ yr}^{-1}} \right).$$

The value of $\beta M_{\text{in}}$ represents an average during the epoch when the WD’s mass is changing.

We now compute the number of NBWDs expected if double-degenerate binaries are the primary class of SNeIa progenitors. This discussion mirrors that in Section 2 of Di Stefano (2010), which computed the number of NBWDs expected if single-degenerate binaries are the primary class of SNeIa progenitors. The rate of SNeIa in galaxies is roughly 0.3 per century per $10^{10} L_\odot$ in blue luminosity (Cappellaro et al. 1993; Turatto et al. 1994; Dilday et al. 2008; Graham et al. 2008; Kuznetsova et al. 2008; Poznanski et al. 2007; Panagia et al. 2007). In a galaxy with blue luminosity, $L_B$, the number, $N_{\text{acc}}$, of pre-double-degenerate SNIa progenitors actively accreting, with masses within 0.1 $M_\odot$ of the value they will have when contact is established is

$$N_{\text{acc}} = 3000 \left( \frac{\Delta M}{0.1 M_\odot} \right) \left( \frac{1 \times 10^{-7} M_\odot \text{ yr}^{-1}}{\beta M_{\text{in}}} \right) \left( \frac{L_B}{10^{10} L_\odot} \right).$$

If double degenerates are the principle progenitors of SNeIa, then we expect that galaxies such as the Milky Way, M31, and other large spirals contain thousands of actively accreting
NBWDs. Note that this counts only the pre-double-degenerates that could eventually become SNeIa. In addition, there are many systems very similar to the supernova progenitors undergoing the same type of evolution, even though the total WD mass will be smaller than \( M_C \). The numbers of NBWDs in galaxies also include those in which there will not be a common envelope producing a close double-degenerate binary.

Elliptical galaxies house older stellar populations and may therefore have smaller values of \( L_B \), even though their total stellar mass may be larger. The rates of SNeIa in early-type galaxies suggest that they should contain \( \sim 1/3 \) as many NBWDs associated with pre-double-degenerates that are progenitors of SNeIa. There should therefore be at least several hundred NBWDs in each elliptical if the double-degenerate channel is the primary route to SNeIa.

It is worth comparing the results above to the parallel results for single degenerates (Di Stefano 2010). The number of NBWDs needed to produce the measured rate of SNeIa via the double-degenerate channel may be larger then the number needed for the single-degenerate channel. The reason is that, even though comparatively little mass may be gained by the WDs in pre-double-degenerates, the WDs are less massive and can burn incoming matter when the infall rate is lower. The interval during which the WD can burn incoming material can therefore be longer. This can produce a larger number of active nuclear burners at one time. There are other differences as well, which we will discuss below.

3.2. Observations

Because there is a link between NBWDs and SSSs, it is important to compare the numbers of NBWDs needed to produce the total rate of SNeIa with the numbers of SSSs observed. The advent of Chandra and XMM-Newton made it possible to detect and identify SSSs in external galaxies at least as far from us as the Virgo cluster. Because extragalactic SSSs provide little flux, individual sources may provide fewer than 50–100 counts with Chandra. With XMM-Newton the count rate is higher, but the number of background counts is also higher. It was therefore important to develop clear and reliable ways to identify SSSs in external galaxies. A small set of nearby galaxies, M31, M101, M83, M51, M104, NGC4472, and NGC4697, served as testbeds for algorithms to identify SSSs (Di Stefano et al. 2003, 2004a, 2004b). When applying and testing our algorithms, we found that, in addition to SSSs, whose spectra cuts off at roughly 1 keV, there are comparably bright X-ray sources that are also soft, but which cut off at somewhat higher energy, roughly 2 keV. These were dubbed quasissort sources (QSSs). (See Di Stefano & Kong 2004; Di Stefano et al. 2004a, 2004b).

Table 1 of Di Stefano (2010) lists the numbers of SSSs in M101, M83, M51, M104, NGC4472, and NGC4697. The numbers of SSSs are, respectively, 42, 28, 15, 5, 5, and 4. M101, M83, and M51 are late-type galaxies. The dominant stellar populations in the bulge-dominated spiral M104, and the ellipticals NGC4472, and NGC4697 are likely to be older. For galaxies of all types, the numbers of SSSs are roughly 2 orders of magnitude smaller than the numbers of NBWDs required if the double-degenerate channel is the primary route to SNeIa.

In fact, the true discrepancy may be larger, because not every SSS observed in these galaxies is likely to be a pre-double-degenerate SNIa progenitor. Some of the SSSs, for example, have luminosities that are too high to be NBWDs. Others are classical novae (Pietsch et al. 2005; Henze et al. 2009), with accretion rates not in the band expected (Section 2). Others are engaged in stable mass transfer and will not produce a common envelope. The true mismatch is therefore likely to be larger than 2 orders of magnitude.

We might ask if it is possible that the NBWDs in the pre-double-degenerate SNIa progenitors could exhibit a hard component in addition to the soft radiation associated with nuclear burning. If so, they might appear as QSSs. The numbers of QSSs detected in M101, M83, M51, M104, NGC4472, and NGC4697 are, respectively, 21, 26, 21, 17, 22, and 15. The populations of QSSs are far too small to make up the difference. In fact, the numbers of X-ray sources that are not either SSS or QSS in these galaxies are, respectively, 24, 74, 56, 100, 184, and 72. Thus, there would still be a shortfall by an order of magnitude, even if all of the X-ray sources were pre-double-degenerate SNIa progenitors.

The mismatch discovered through the study of the six galaxies mentioned above holds as well for M31, and for all 383 external galaxies observed with Chandra and studied by Liu (2008). Other investigations of X-ray sources in external galaxies also give results that are consistent with there being a relatively small number of very soft sources. (See, e.g., Sarazin et al. 2001; Swartz et al. 2002; Pence et al. 2001; Jenkins et al. 2005; Fabbiano et al. 2003).

4. THE SIGNIFICANCE OF THE MISMATCH

4.1. Is The Mismatch Real?

In assessing the significance of this mismatch, it is important to address the question of whether the extragalactic NBWDs in pre-double-degenerate binaries are bright and hot enough to be detected as SSSs. We have already addressed this question for the NBWDs in single-degenerate progenitors of SNeIa (Di Stefano 2007, 2010; Di Stefano et al. 2010). In single-degenerate models, the WDs must have mass close to \( M_C \) prior to explosion. As they gain the mass needed to bring them to the limit, they will be the brightest and hottest NBWDs, with luminosities near the Eddington limit and effective values of \( kT \) over \( \sim 80 \) eV. In several nearby galaxies, X-ray observations conducted to date would have been able to provide a complete census of such NBWDs with \( N_H \) in the range of a few times \( 10^{21} \) cm\(^{-2} \). The mismatch is therefore highly significant and has been known for some time.

The accreting WDs in pre-double-degenerates will generally not have masses near \( M_C \). In general, though, we expect that the first WD to form will be the more massive of the two WDs that eventually merge. Its mass must therefore be larger than 0.7 \( M_\odot \), and is likely to be larger than 0.8–0.9 \( M_\odot \). Although they will not be as hot and bright as more massive WDs, NBWDs in this mass range can be detected in external galaxies. Figure 2 of Di Stefano (2010) shows that the count rate expected from a WD of 0.9 \( M_\odot \) in M31 would allow it to be detected by Chandra, even with an \( N_H \) of a few times \( 10^{20} \) cm\(^{-2} \). WDs of 0.8 \( M_\odot \) would be detected in M31 with \( N_H \sim 10^{21} \) cm\(^{-2} \). Several M31 fields have been well studied at soft X-ray wavelengths with Chandra, most notably the bulge, which has the highest density of soft sources. While XMM-Newton may not be able to resolve all of the sources near the nucleus, it has provided the advantage of wide-area coverage. With deep surveys of the body of M31, XMM-Newton should have discovered all of the NBWDs with

2 Of course, most of the bright non-SSS and non-QSS sources we detect in other galaxies are likely to be accreting neutron stars or black holes, just as is the case in the Local Group.
identified dozens of SSSs. Only a handful were identified as degen-

erates. If, therefore, the double-degenerate channel is the likely
to include at least a few percent of the Galactic pre-double-
luminosity expected for a WD with 0.8\,M⊙.

Masses above 0.8\,M⊙. The combined results from Chandra (Di Stefano et al. 2004) and XMM-Newton (Orio 2006) show that the number of SSSs detectable at any given time is more than an order of magnitude smaller than the number predicted by Equation (3). In addition, deep observations by Chandra of the face-on galaxy M101 have been taken (>1 Ms); the analysis of Liu (2008) finds no evidence of large enough numbers of SSSs or QSSs.

Finally, although gas in the Galactic disk prevents us from
detecting many SSSs, Figure 2 shows that the ROSAT All-Sky Survey (RASS) would have detected many Galactic NBWDs with masses of 0.9\,M⊙ or 0.8\,M⊙, if they emit soft X-rays with the expected luminosities and temperatures. Excluding regions with high N_H, including star-forming regions and the direction toward the Galactic center, NBWDs with the temperature and luminosity expected for a WD with 0.9\,M⊙ (0.8\,M⊙) could be identified if they lie within ∼6 (−3) kpc. These regions are likely to include at least a few percent of the Galactic pre-double-degenerates. If, therefore, the double-degenerate channel is the main route to SNeIa, we expect that the RASS would have identified dozens of SSSs. Only a handful were identified (Greiner 2000).

To summarize, data from several galaxies, including our own, seem to indicate that the numbers of SSSs are too small by at least 2 orders of magnitude to support the hypothesis that (1) the double-degenerate channel is the dominant way to produce SNeIa, and that (2) the winds incident on the first-formed WD prior to the common envelope phase cause nuclear burning, and (3) the NBWDs can be detected and identified as SSSs.

It is important to note, however, that the limits on the numbers of SSSs that could correspond to WDs in the mass range corresponding to pre-double-degenerates are not as strong as the limits for the near-M⊙ WDs expected in the single-degenerate model. Therefore, more work is needed to determine the fraction of SSSs, as a function of luminosity and temperature, that can be detected in each of several nearby galaxies. Work that parallels the early calculations (Di Stefano & Rappaport 1994) is needed. Specifically, the gas distributions of nearby galaxies can be modeled. The galaxies themselves can then be seeded with SSSs, each with a given luminosity and temperature. The numbers of counts expected from each SSS during observations with Chandra and XMM-Newton can then be computed to determine whether the source would have been detected and, if so, whether there are enough photons to determine that it is an SSS. In this way, we can determine the fraction of SSSs that can be identified in each galaxy as a function of luminosity and temperature. We can then discover how many sources are obscured by interstellar absorption.

4.2. Implications of the Mismatch

What does the lack of SSSs tell us about the progenitors of SNeIa? To answer this question, we consider in turn each of the possibilities listed above.

1. Perhaps the double-degenerate channel is not the dominant way to produce SNeIa. In other words, the lack of SSSs is a sign that the NBWDs needed for the double-degenerate model simply do not exist.

   We note here, however, that this conclusion does not follow simply from the fact that there are too few SSSs. In fact, if we combine the result above for double degenerates with the result of Di Stefano (2010) for single degenerates, and also assume that the lack of SSSs is due to the lack of NBWDs, then all models of SNeIa involving WDs that accrete and process matter are eliminated.

2. Perhaps the winds incident on the first-formed WD prior to the common envelope phase do not cause nuclear burning. There are two possibilities: (a) the winds are not incident at the required rate or (b) the steady-burning regime does not exist.

   (a) As Figure 1 demonstrates, the rate of wind infall is in or near the steady-burning regime for a wide range of assumptions about winds, the fraction of winds captured, and the exact boundaries of the steady-burning regime. The only way that the wind infall could not be adequate is if winds from the giant can be deflected by radiation and/or winds from the WD. In order for this to occur, however, the WD must be generating a great deal of energy, perhaps suggesting that nuclear burning must occur.

   (b) The existence of the nuclear-burning regime has been questioned (see, e.g., Starrfield et al. 2005). Nevertheless, independent calculations by a number of groups find that quasi-steady nuclear burning is possible; furthermore there is rough agreement on the locations of the upper and lower boundaries of the steady-burning regime (Iben 1982; Nomoto 1982; Shen & Bildsten 2007). On general grounds, it seems likely that quasi-steady nuclear burning should occur over some range of infall conditions, since it should be possible for accretion at high rates to produce conditions similar to those found near the cores of giants.

3. Perhaps only a small fraction of NBWDs can be detected and identified as SSSs. This seems to be the most likely possibility. First, circumstellar material can reprocess the ultraviolet and soft X-ray radiation, producing radiation at longer wavelengths. In symbiotics, the winds from the giant can play this role. In fact, symbiotic nebulae are common (see, e.g., Kenyon 2000). Second, the duty cycle of nuclear burning can be low, as it is for recurrent novae. In the next section, we consider a range of measurable signatures for pre-double-degenerates, such as orbital period and stellar age.
5. SYMBIOTICS AS PRE-DOUBLE-DEGENERATES

We have shown that many double-degenerate binaries are descended from binaries in which the first-created WD accretes and burns matter from a giant stellar companion. These binaries are symbiotics. (See Kenyon 2000, and references therein.) It is possible that some of the known symbiotics are headed toward double-degenerate futures. It will be important to identify such systems. To do so, we must establish whether the giant will come to fill its Roche lobe. If so, will the relative masses and rates of mass and angular momentum loss be such as to trigger a common envelope? Finally, will the total WD mass exceed the Chandrasekhar mass?

The calculations that produced Figure 1 can be used to study the properties of the pre-double-degenerates that are progenitors of SNeIa. Each point in Figure 3 represents such a binary in which the total WD mass is greater than $M_C$. Green (red) points correspond to systems in which the WD gains more than 0.15 $M_\odot$ (less than 0.05 $M_\odot$). Extended periods of nuclear burning may occur in most or all of these systems. For example, 10$^7$ years are required for a WD to gain 0.05 $M_\odot$ at an average rate of $5 \times 10^{-7} \ M_\odot$ yr$^{-1}$. Systems in which more mass is gained, however, must burn material more quickly and therefore be brighter, and/or must burn material over a longer period of time and therefore be potentially detectable for a longer duration. The top panel of Figure 3 shows that the systems which gain more mass tend to have larger orbital periods: longer than five years for WDs gaining more than 0.15 $M_\odot$, although mass can be gained by WDs in binaries with shorter orbital periods. The bottom panel shows that the longer orbital periods for systems in which more mass is transferred are associated with the fact that the giant donor in such systems becomes more evolved, achieving a larger core mass and radius before the common envelope is triggered. Interestingly enough, these are the systems in which the two WDs that eventually merge will have a total mass well over $M_C$.

Also shown in Figure 3 is the lifetime, $\tau$, of star “2,” the star that became the giant donating mass to the WD. The value of $\tau$ is roughly equal to the time after the formation of the binary when the nuclear-burning activity occurs. From the perspective of detectability, we find that many progenitors will experience periods of nuclear-burning activity at times earlier than a few times 10$^8$ years after formation; these systems will be found near regions of star formation. In systems that gain the most mass, star “2” will generally have finished its epoch of mass transfer by 10$^9$ years after formation. On the other hand, nuclear-burning activity may occur at late times in binaries in which the WD gains less mass. Note that the value of $\tau$ is also a measure of the initial mass of the secondary. Those double degenerates in which the total WD mass will be largest are formed from systems that experience an epoch of nuclear burning before roughly 10$^8$ years; both stars must start with masses larger than a few $M_\odot$; the orbital period just prior to the common envelope can be longer than 20 years.

Figure 4 shows the evolution of some individual binaries in our simulation in which the total WD mass will exceed $M_C$. We can use this figure to gain additional insight into the possible appearance of the symbiotics that are progenitors of SNeIa through the double-degenerate channel. In this figure, $t = 0$
would correspond to the time at which the common envelope is triggered; \( \tau \) is therefore the time prior to the common envelope. The bottom panels show \( M_{\text{in}} \) versus \( \log(\tau) \). The black curves correspond to the steady-burning region. The top panels show the loss of the giant’s mass through winds, the growth of its core mass, and the growth of the mass of the accreting white dwarf. All of the systems start with such small winds that \( M_{\text{in}} \) is in the nova range; the WD gains no mass during the early stages of mass transfer. As winds increase, the WDs enter the range of mass infall rates associated with recurrent novae. The system on the left stays in this region for \( \sim 10^6 \) years; the WD gains only a small amount of mass. The system in the middle panels passes through the recurrent nova region in roughly \( 10^6 \) years and then spends a comparable amount of time in the steady-burning regime. The mass increase of the WD is somewhat larger. In the set of panels on the left, the mass infall rate increases beyond the steady-burning regime, and the system spends significant time in all three mass-gain regions (recurrent nova; steady burning; and in the region above steady burning, expected to be associated with heavier winds).

During the recurrent nova phase, the duty cycle of nuclear burning and of potential detection as an SSS is small. For systems like RS Ophiuchi, it can be on the order of a percent (see, e.g., Nelson et al. 2009). Low duty cycle can help to explain the small observed numbers of SSSs; systems like the one shown in the leftmost panels have a low probability of being detected in a nuclear-burning state. On the other end of the scale, accretion at very high rates can mean that the circumstellar region is dense, so that soft X-rays and EUV radiation are absorbed and reprocessed. Systems like the one shown in the right-hand panels may not be detectable as SSSs.

Figure 5, produced by the same simulation, shows the duration, \( t_{\text{active}} \) of nuclear-burning activity versus \( \tau \), the time at which the activity starts. The systems in the top (bottom) panels produce double degenerates with total WD mass greater (less than) \( M_C \). As in Figure 4, we consider separately the regimes (1) below \( M_{\text{min}} \), where recurrent novae are expected (panels on the left), (2) the steady-burning regime (panels in the middle), and (3) the regime of infall rates greater than \( M_{\text{max}} \) (panels on the right). A difference between Figures 5 and 4 is that each panel in Figure 4 shows the evolution of an individual binary, while Figure 5 summarizes what happens during the evolutions of all binaries in the simulation. In addition, all binaries that enter the steady-burning regime start in the recurrent nova regime. Thus, each point in the middle panel also corresponds to a point in the panel to the left of it. Similarly, each point in the “heavy winds” panels also corresponds to a point in the steady-burning panel, and also to a point in the “recurrent nova” panel. Figure 5 verifies that, for many systems, the duration of nuclear-burning activity is long, in excess of \( 10^6 \) years. It shows that systems in which the mass accretion rate is above the steady-burning regime should end their activity within a few times \( 10^5 \) years after they are formed; this is because the mass of the donor star tends to be large. This figure also demonstrates that significant nuclear-burning activity is expected from those pre-double-degenerates that cannot become SNeIa, because the total WD mass is too low. WDs in these binaries can become active nuclear burners \( \sim 10^6 \) years after star formation. We may expect to find them in elliptical galaxies and other old stellar populations.

The common envelope phase ends the symbiotic epoch takes a relatively short time, \( \sim 10^5 \) years to dissipate. The orbital separation at the end of the common envelope phase determines the amount of time required for the WDs to come close enough to each other for mass transfer and merger to occur. Depending on the efficiency of common envelope ejection in each binary, the interval between the nuclear-burning phase and the supernova could be shorter than \( 10^6 \) years, or longer than the Hubble time.

6. CONCLUSION

We have shown that many pre-double-degenerate binaries pass through an epoch during which the first-formed WD accretes and burns matter from a giant companion. If double degenerates with total WD mass greater than \( M_C \) comprise the major component of SNeIa progenitors, then the numbers of symbiotics with NBWDs must be on the order of a thousand in galaxies such as our own. If the nuclear-burning episodes produce SSS-like signatures, then we should be able to identify the pre-double-degenerate progenitors of SNeIa in other galaxies by identifying SSSs. In Section 4.1, we have sketched the steps needed to determine the numbers of SSSs in external galaxies that have the luminosities and temperatures predicted for the pre-double-degenerate progenitors of SNeIa. Already, however, data from M31, M101, more than 380 additional galaxies, and from the Milky Way strongly indicate that there is a mismatch of \( \sim 2 \) orders of magnitude between the predicted numbers of SSSs and the numbers we actually detect in other galaxies. The result holds for young and old stellar populations.

We have already derived an even stronger result for single-degenerate progenitors of SNeIa (Di Stefano 2007, 2010; Di Stefano et al. 2010). We falsified the hypothesis that the
single-degenerate channel in which WDs accrete and burn enough matter to reach $M_C$ is the primary progenitor channel and that the NBWDs appear as SSSs.\textsuperscript{3} Combining the results for double degenerates and single degenerates, we find that there are not enough SSSs in our own and other galaxies to explain the observed rates of SNeIa. Since the supernovae occur, the implication is that there is a disconnect between either (1) mass infall at high rates and nuclear burning, or (2) nuclear burning and SSSs.

1. If mass infall does not lead to nuclear burning, this would seem to imply that a change is needed in our understanding of fundamental astrophysics. An alternative is that when nuclear burning does occur, enough energy is released to deflect winds, providing a kind of thermostat mechanism.

2. Mass accretion and nuclear burning are not always linked to SSS-like behavior. This is already known to be the case for many systems. For example, the duty cycle of SSS-like behavior is low for recurrent novae; some of these, such as RS Ophiuchi are symbiotics (Nelson et al. 2009, and references therein). In addition, absorption is expected because winds from symbiotics can absorb radiation from the WD. In fact, the nebulae associated with symbiotics illustrate this point (see, e.g., Kenyon 2000).

With regard to the question of “hiding” the progenitors of SNeIa, symbiotics are intriguing for three reasons. First, of course, is the likelihood that at least some symbiotics are progenitors of SNeIa. In this paper, we have focused on pre-double-degenerates that may be SNIa progenitors. Even among single degenerates, however, there are models in which the progenitor passes through a phase in which a giant donates mass to a WD either through winds or through Roche lobe overflow (Di Stefano 1996).

Second, symbiotics are examples of very bright systems that have proved difficult to identify. Estimates of the numbers of Galactic symbiotics are as high as $4 \times 10^4$ (Magrini et al. 2003). In spite of these large numbers, and in spite of the fact that symbiotics are, by their very natures highly luminous, the numbers of known symbiotics had stood in the low hundreds until recently. Within the past several years, $\sim 1000$ candidates, now being checked, have been identified (see Corradi et al. 2010). Whatever the appearance of the progenitors of SNeIa, they too must be very bright, at least during episodes of nuclear burning. They too appear to be underrepresented, in that too few candidates have been identified in our Galaxy and in other galaxies. Third, whether or not specific symbiotic binaries are SNIa progenitors, many contain NBWDs. The low numbers of SSSs we find are therefore relevant for understanding the appearance of symbiotics.

**Summary.** The key issue identified by the study of galaxy populations of SSSs is that there are too few of them to serve as the progenitors of SNeIa. This applies to early-type and late-type galaxies. It applies to single-degenerate and double-degenerate models. To understand the progenitors of SNeIa, we must be able to predict the appearance of NBWDs and to identify a larger fraction of them in our own and other galaxies.

\textsuperscript{3} A similar result was claimed for old stellar populations based on limits on the diffuse soft emission from the bulge of M31 and several early-type galaxies (Gilfanov & Bogdán 2010). In these cases, however, the bright, hot NBWDs with masses near $M_C$ would have been detected directly had they been there, so the previously existing limits apply.

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**APPENDIX:**

**CAN THE MISMATCH BETWEEN THEORY AND OBSERVATION BE SMALLER?**

**A.1. The Width of the Nuclear-burning Region**

Calculations by a number of different groups find that for each WD mass there is a range of values of $M_\text{in}$ for which incoming material can be burned in a quasi-steady manner. Although there is general agreement that quasi-steady nuclear burning occurs, there is some disagreement about the value of the minimum rate needed and also about the width of the steady-burning region. (See, e.g., Cassisi et al. 1998; Piersanti et al. 2000; Shen & Bildsten 2007; Nomoto et al. 2007.) In fact, physical features such as different metallicities can affect the placement and width of the steady-burning region (Piersanti et al. 2000). At least some calculations show a significant narrowing of the steady-burning region, particularly for WD masses near $M_C$.

The range of WD masses most relevant to pre-double-degenerates is the range between roughly $0.7 M_\odot$ and $1 M_\odot$. In this range, the calculations generally agree, at least to within a factor of a few. Figure 1 shows the distribution of values of $M_\text{in}$ as a function of WD mass for pre-double-degenerates. The uniform distribution of points assures that the narrowing of the burning region by a factor of a few would have the effect of reducing the numbers of NBWDs by a comparable factor. If therefore, the true width of the quasisteady-nuclear-burning regime is roughly comparable to the computed values, the mismatch between the numbers of NBWDs expected in double-degenerate models and the numbers of SSSs observed is still at least a factor of 10.

There is a separate question of whether matter burned by the WD is retained. As we mentioned in the body of the paper, mass retention could allow some WDs to gain enough mass that the double-degenerate has a total mass greater than $M_C$, even though the total WD mass would have been smaller than $M_C$ otherwise. It is possible that mass loss following He flashes will cause the external layers to expand, allowing some mass to be lost (see, e.g., Kato & Hachisu 1999). This would not strongly affect the duty cycle of nuclear burning and does not therefore alter the main result of this paper.

**A.2. Old Populations**

It may be the case that, in some stellar populations, the numbers of NBWDs associated with double-degenerate Type Ia progenitors are small. In fact, one might expect older populations to be depleted in those NBWDs that are pre-double-degenerates. In a separate paper, we describe simulations to compute the number of NBWDs as a function of stellar age. Here, we make a general argument.

The crucial element is the wait time between stellar formation and the NBWD phase. This wait time is the stellar lifetime of the binary’s secondary star. In order for a common envelope to form when this star fills its Roche lobe as a giant, it must be more massive than its WD companion. As mentioned
above, the WDs in systems that eventually experience double-degenerate mergers with a total mass greater than $M_C$ are likely to have masses greater than $0.7 M_\odot$. This suggests that the original mass of the secondary should not be very much smaller than $1.5-2 M_\odot$. Stellar formation must have occurred within roughly 4 Gyr.

Apart from globular clusters, most stellar populations include intermediate-age and/or young stars. We know, e.g., that the central region of our own Galaxy contains massive young stars (see, e.g., Schödel et al. 2009; Ghez 2007; Ghez et al. 2005; Genzel et al. 2003). Studies of elliptical galaxies find evidence of ongoing star formation (Salim & Rich 2010, and references therein). Even the outer bulge/inner halo of M31 contains intermediate-age stars (e.g., Brown et al. 2003). Therefore, while the fraction of systems that are pre-double-degenerate NBWDs may be lower in older populations, some such systems should nevertheless exist. In addition, there should be an even larger number of WDs accreting, both from giants and main-sequence stars (the latter with masses of $1-2 M_\odot$) at rates that put them in the steady-burning regime, even though the binary will not become an SNII.

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4 The secondary star may have gained some mass from winds emitted by the primary before it filled its Roche lobe. In this case, the secondary star could be somewhat older than its mass suggests. This is, however, likely to be a small effect.