THE MERGER RATE OF BINARY WHITE DWARFS IN THE GALACTIC DISK

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ABSTRACT

We use multi-epoch spectroscopy of ~4000 white dwarfs in the Sloan Digital Sky Survey to constrain the properties of the Galactic population of binary white dwarf systems and calculate their merger rate. With a Monte Carlo code, we model the distribution of \( ARV_{\text{max}} \), the maximum radial velocity shift between exposures of the same star, as a function of the binary fraction within 0.05 AU, \( f_{\text{bin}} \), and the power-law index in the separation distribution at the end of the common-envelope phase, \( \alpha \). Although there is some degeneracy between \( f_{\text{bin}} \) and \( \alpha \), the 15 high-\( ARV_{\text{max}} \) systems that we find constrain the combination of these parameters, which determines a white dwarf merger rate per unit stellar mass of \( 1.4^{+3.4}_{-1.0} \times 10^{-13} \) yr\(^{-1} \) \( M_{\odot}^{-1} \) (1\( \sigma \) limits). This is remarkably similar to the measured rate of Type Ia supernovae (SNe Ia) per unit stellar mass in Milky-Way-like Sbc galaxies. The rate of super-Chandrasekhar mergers is only \( 1.0^{+1.6}_{-0.6} \times 10^{-14} \) yr\(^{-1} \) \( M_{\odot}^{-1} \). We conclude that there are not enough close binary white dwarf systems to reproduce the observed SN Ia rate in the “classic” double degenerate super-Chandrasekhar scenario. On the other hand, if sub-Chandrasekhar mergers can lead to SNe Ia, as has been recently suggested by some studies, they could make a major contribution to the overall SN Ia rate. Although unlikely, we cannot rule out contamination of our sample by M-dwarf binaries or non-Gaussian errors. These issues will be clarified in the near future by completing the follow-up of all 15 high-\( ARV_{\text{max}} \) systems.

Key words: binaries: close – white dwarfs – supernovae: general

Online-only material: color figures

1. INTRODUCTION

The nature of the progenitor systems of Type Ia supernovae (SNe Ia) remains one of the key open issues in stellar evolution. There is a general agreement that the exploding star is a CO white dwarf (WD) that is somehow ignited following accretion of material from a binary companion, but the identity of this companion is still a matter of debate. Most theoretical scenarios for SN Ia progenitors can be divided into two broad classes: single degenerate (SD) systems (Whelan & Iben 1973), where the companion is a non-degenerate star and material is transferred over \(<1 \text{ Myr via Roche lobe overflow or wind accretion, and double degenerate (DD) systems (Iben & Tutukov 1984; Webbink 1984), where the companion is another WD and mass transfer happens over much shorter timescales in a merger event.}

Recent developments have provided some evidence in favor of the DD scenario. Sensitivity searches have failed to find signs of a mass-losing non-degenerate companion in radio observations (Horesh et al. 2012; Chomiuk et al. 2012), early light curves (Hayden et al. 2010; Bianco et al. 2011; Bloom et al. 2012), and supernova remnants (Badenes et al. 2007; Schaef er & Pagnotta 2012, but cf. Williams et al. 2011, and see Sterberg et al. 2011 for some statistical evidence of absorption in SN Ia spectra that could be of SD origin). Several independent measurements of the delay time distribution (the specific rate of SNe Ia as a function of time after a hypothetical brief burst of star formation) have converged onto a \( \sim t^{-1} \) shape extending from a few hundred Myr to several Gyr (see Maoz & Mannucci 2011, for a recent review), a form expected from a population of DD systems that merge due to gravitational wave emission.

In this Letter, we present the first measurement of the local WD merger rate and use it to test the viability of the DD scenario for SN Ia progenitors. To date, orbital parameters have been measured for over 40 individual DD systems with periods ranging between 12 minutes (Brown et al. 2011b) and several days (e.g., Marsh et al. 1995; Nelemans et al. 2005; Kilic et al. 2010), but the fundamental properties of the Galactic DD population are still poorly known. Some small WD samples have been used to estimate parameters like the binary fraction (Maxted & Marsh 1999 find it to be between 0.017 and 0.19, based on 46 WDs) or the merger rate limited to systems that contain extremely low mass (<0.25 \( M_{\odot} \)) WDs (\(<4 \times 10^{-5} \) yr\(^{-1} \) based on 12 systems; Brown et al. 2011a). Here, we adopt a statistical approach to characterize the DD population, using the unique capabilities of the Sloan Digital Sky Survey (SDSS) for time resolved spectroscopy of thousands of WDs. We use this large data set to measure the distribution of \( ARV_{\text{max}} \), the maximum radial velocity (RV) shift between exposures of the same WD. In a companion paper (Maoz et al. 2012, henceforth Paper I), we describe how this distribution constrains the binary fraction and the separation distribution. Because the evolution of detached DD systems is driven only by gravitational wave emission, these parameters, together with the WD masses, uniquely determine the local merger rate, which can be compared to measurements of the specific SN Ia rate in nearby Milky-Way-like galaxies.

2. OBSERVATIONS

The SDSS (York et al. 2000) contains the largest available collection of WD spectra (Kleinman et al. 2004; Eisenstein et al. 2006). The latest version of the SDSS WD catalog, corresponding to DR7, has over 17,000 entries (Kleinman et al. 2009). For simplicity, we have restricted our analysis to non-magnetic DA WDs that show no obvious signs of main-sequence

An unpublished version of the catalog containing 17,371 entries was made available to us by S. Kleinman in 2010 July.
companions, and have no confirmed or possible absorption lines from any elements other than H—i.e., objects classified as “DA” or “DA:” in the catalog. We further removed from this sample any elements other than H—i.e., objects classified as “DA” companions, and have no confirmed or possible absorption lines from any elements other than H—i.e., objects classified as “DA” or “DA:” in the catalog. We further removed from this sample seven WDs with main-sequence companions listed by Rebassa-Mansergas et al. (2012), leaving 12,763 objects.

Like all SDSS spectra, the spectra of these WDs were divided into three or more sub-exposures to facilitate cosmic-ray rejection (Stoughton et al. 2002). Since DR7 (Abazajian et al. 2009), these sub-exposures are available from the SDSS server. The ongoing SW ARMS survey is using these sub-exposures to identify short-period binary WD candidates in SDSS, which are then followed up (Badenes & Maoz 2011; Mullally et al. 2009). The DS/DT collaboration (Bickerton et al. 2011) has implemented a pipeline to handle cosmic-ray rejection and derive stable wavelength solutions for all sub-exposures of the same object. This Letter presents the first results obtained using the DS/DT pipeline—see Bickerton et al. (2011) for technical details.

To measure RVs, we normalize each spectrum, dividing it by a highly smoothed version of itself, and we fit four Balmer lines—Hα through Hγ—with Voigt profiles in absorption. We find the best-fit model for each line using MPFIT (Markwardt 2009), an IDL implementation of the Levenberg–Marquardt algorithm. For each sub-exposure $n$, these fits yield four RV measurements $RV_{n,i}$, and four 1σ errors $\delta RV_{n,i}$ ($i = 0..3$). To define a single RV for each sub-exposure, we impose a threshold on the error of individual RV measurements, $\delta RV_{n,thr}$, and discard values with larger errors or that deviate by $>1\sigma$ from the weighted mean, $RV_n = (\sum_i w_{n,i} \times RV_{n,i}) / \sum_i w_{n,i}$, with $w_{n,i} = 1/\delta RV_{n,i}$. In sub-exposures with at least two surviving RVs, we re-calculate the weighted mean RV$_n$ and define its error as $\delta RV_n = \sqrt{\sum \delta RV_{n,i}^2}$. Finally, we define $\Delta RV_{max}$ as the difference between the highest and lowest RV$_n$ in each object. This procedure eliminates noisy sub-exposures with internally inconsistent RVs, effectively culling most WDs fainter than $g \sim 19$. We find that $\delta RV_{thr} = 80 \text{ km s}^{-1}$ gives a good compromise between sample size and quality, with 4063 WDs and 15,236 RV measurements. The distribution of RVs and $\delta RV$s in this sample is shown in Figure 1. The mean of the RV distribution, $31.0 \pm 0.4 \text{ km s}^{-1}$, is nonzero and positive due to gravitational redshift at the WD surfaces. This is the expected value for a local WD population with an average mass of $\sim 0.6 M_{\odot}$, and confirms the $32.6 \pm 1.2 \text{ km s}^{-1}$ redshift obtained by Falcon et al. (2010) using a different sample of 449 DA WDs observed at high resolution ($\sim 16 \text{ km s}^{-1}$ pixel$^{-1}$; see Napierwotzki et al. 2001—for comparison, SDSS spectra are $\sim 70 \text{ km s}^{-1}$ pixel$^{-1}$). The agreement shows that our procedure yields well-calibrated RVs, and that the DS/DT pipeline successfully removes the systematic redshifts noted by some authors in SDSS spectra.

A key ingredient in the Monte Carlo models described in Section 3 and Paper I is the distribution of errors, $\delta RV$. We therefore estimate the errors independently, and compare them to the errors reported by MPFIT. For each Balmer line of each WD, we find the difference between random pairs of RVs that have similar reported values of $\delta RV$. These differences have an approximately Gaussian distribution, with a $\sigma$ that gives an
empirical estimate of the true error in the RV measurements, times $\sqrt{2}$. Using this procedure, we find that MPFIT tends to underestimate the RV errors. We obtain the corrected $\delta$ RV distribution shown in Figure 1 by running a grid of such pair subtraction tests.

3. THE WD MERGER RATE

The distribution of $\Delta RV_{\text{max}}$ values in the $\delta RV_{\text{true}} = 80$ km s$^{-1}$ sample is shown in Figure 2. The vast majority of WDs have low $\Delta RV_{\text{max}}$—these are either isolated WDs or DD systems where the data show no evidence for significant RV shifts because the period is too long, or the inclination is too small, or the sub-exposures were taken at similar orbital phases. However, there is a significant tail of WDs with high $\Delta RV_{\text{max}}$, extending beyond 500 km s$^{-1}$. From the distribution of SDSS sampling times and RV errors, we do not expect any non-binary WDs to have $\Delta RV_{\text{max}}$ higher than $\sim 250$ km s$^{-1}$ (dashed line in Figure 2—see Paper I for details). The 15 objects with higher $\Delta RV_{\text{max}}$ are therefore real binaries, detected at high significance. Some of these are already published discoveries, like SDSS 1257 ($\Delta RV_{\text{max}} = 538$ km s$^{-1}$, Badenes et al. 2009), or SDSS 0923 ($\Delta RV_{\text{max}} = 410$ km s$^{-1}$; Brown et al. 2010). Others will be the subject of forthcoming papers.

At intermediate values of $\Delta RV_{\text{max}}$, between $\sim 200$ and 300 km s$^{-1}$, follow-up observations are necessary to tell which of the several dozen WDs are real binaries, but here we are only concerned with the statistics of the $\Delta RV_{\text{max}}$ distribution, not the binary character of individual systems. As a precaution, we have visually vetted the spectra of the 107 WDs with $\Delta RV_{\text{max}} \geq 175$ km s$^{-1}$ to check for any misclassified objects, WDs with weak line emission, spurious line fits, etc., and removed them from the distribution.

The Monte Carlo techniques that we use to model the $\Delta RV_{\text{max}}$ distribution are described in detail in Paper I. The method involves generating a large number of WD systems with a given binary fraction, drawing the binary separation, $a$, and the component masses from given distributions, assigning random inclinations and phases, choosing the photometric primary, and folding the resulting RV curves through the observational parameters (sampling times and $\delta$ RV distribution) of the SDSS data. Because we can only detect binaries at high confidence with $\Delta RV_{\text{max}} \gtrsim 250$ km s$^{-1}$, there is an upper limit to the separations that we can probe. For an extreme-mass-ratio WD pair with $M_1 = 1.1 M_\odot$ and $M_2 = 0.2 M_\odot$, an RV curve with a peak-to-peak amplitude of 250 km s$^{-1}$ corresponds to a separation of $\sim 0.05$ AU. Therefore, we define the measured binary fraction, $f_{\text{bin}}$, as the fraction of WDs with companions within $a_{\text{max}} = 0.05$ AU. As explained in Paper I, our definition of $f_{\text{bin}}$ does not include an additional population of extremely low mass binaries with primaries below 0.25 $M_\odot$, which we assume are always in short-period binaries (see Brown et al. 2011a and references therein). To constrain the distribution of binary separations, we model it as a power law with index $\alpha$ at the end of the final common-envelope episode, $n(\alpha) \propto \alpha^\beta$. In Paper I, we derive analytically the time-evolved form of this distribution due to gravitational wave emission and merger events, integrated over the star formation history of the Galaxy. This evolved separation distribution is used for generating the simulated WD pairs. Primary masses are chosen from the observed distribution of isolated WDs in Kepler et al. (2007). Secondary masses are chosen from a power-law mass-ratio distribution of index $\beta$. In practice, the results have a weak dependence on $\beta$ and on other details on the component mass distributions (see Paper I for details), and the analysis we present here assumes $\beta = 0$. We choose the photometric primary by random draw, except for $<0.35 M_\odot$ secondaries, which we assume are always photometric primaries (see Paper I).

Each combination of $f_{\text{bin}}$ and $\alpha$ leads to a predicted $\Delta RV_{\text{max}}$ distribution in the survey. Examples of such model distributions are plotted alongside the observed one in Figure 2. This plot showcases the discriminating power of the $\Delta RV_{\text{max}}$ distribution, in that some combinations of $f_{\text{bin}}$ and $\alpha$ are allowed by the data, and some are clearly ruled out. The validity of each model can be quantified by multiplying the Poisson probabilities of finding the observed number of systems in each $\Delta RV_{\text{max}}$ bin, given the expectation from the model. In all comparisons between models and observations, we use only the $\Delta RV_{\text{max}}$ bins above 250 km s$^{-1}$ (15 systems in total).

The likelihoods of different WD population models are shown in Figure 3, with the 95% and 68% confidence level contours...
marked. Lower binary fractions require more negative values of \( \alpha \) to reproduce the observations, and vice versa. This is because the tail of WDs at high \( \Delta V_{\text{max}} \) (i.e., short-period binaries) can result either from WD populations where many binaries are formed at all separations (high \( f_{\text{bin}} \), more positive \( \alpha \)), or few binaries are formed but with preferentially small separations (low \( f_{\text{bin}} \), more negative \( \alpha \)). Some population models can be ruled out using simple arguments. We can require, for instance, that \(<100\%\) of WDs have a companion with \( P < 12 \) days (the circularization limit), which would be in conflict with main-sequence binary surveys (e.g., Raghavan et al. 2010). We can also require that WDs do not merge faster than they are formed because we do observe pre-merger systems. These two conditions rule out the striped regions in the \( f_{\text{bin}}, \alpha \) plane marked in Figure 3.

Every simulated system has a known merger time, and therefore it is straightforward to obtain the merger rate for each simulated binary population, whether in total, or for specific cases, such as super-Chandrasekhar systems. The merger rate per WD in the sample can be converted to a merger rate per unit stellar mass in the solar neighborhood using measured estimates of the local WD number density (Sion et al. 2009) and stellar mass density (McMillan 2011). Curves of constant WD merger rate per unit stellar mass are shown in Figure 3. As explained in Paper I, the curves appear as straight lines in \( \alpha - \log(f_{\text{bin}}) \) space. The slope of the solid lines (all mergers) is \( 1/\log(a_{\text{max}}/a_0) \approx 1.5 \), where \( a_{\text{max}} = 0.05 \) AU, and \( a_0 \approx 0.011 \) AU is the initial separation of a typical WD binary that merges in 1 Gyr (our assumed age of the Galaxy; see Paper I). Offsets in \( \alpha \) between merger rates separated by a decade are also 1.5. Despite the broad range of allowed \( \alpha \) and \( f_{\text{bin}} \) values, the SDSS data put stronger constraints on the specific WD merger rate. The likelihood-weighted merger rate is \( 1.4 \times 10^{-13} \) yr\(^{-1} \) M\(_{\odot}\)\(^{-1} \) for all systems, and \( 1.0 \times 10^{-14} \) yr\(^{-1} \) M\(_{\odot}\)\(^{-1} \) for super-Chandrasekhar systems. Table 1 gives 95% confidence levels on these rates, and allowed ranges of \( f_{\text{bin}} \) for specific values of \( \alpha \).

### 4. DISCUSSION AND CONCLUSIONS

Li et al. (2011) have recently measured the SN Ia rate in galaxies of various Hubble types. For Sbc spirals with the stellar mass of the Milky Way \((16.4 \pm 0.6) 	imes 10^{10} M_{\odot};\) McMillan 2011), the specific SN Ia rate is \( 1.1 \times 10^{-13} \) SNe yr\(^{-1} \) M\(_{\odot}\)\(^{-1} \). This number is remarkably close to our measured specific WD merger rate, but an order of magnitude higher than the super-Chandrasekhar merger rate.

The implication is that there are not enough super-Chandrasekhar DD systems in our local region of the Milky Way to reproduce the measured SN Ia rate through the classical DD channel. Several authors have already pointed out the apparent dearth of super-Chandrasekhar SN Ia progenitors using qualitative arguments (e.g., Isern et al. 1997; Maoz 2008; Ruiter et al. 2009). Our analysis shows this from a quantitative measurement of pre-merger WD binaries. However, we find a remarkable agreement between the total WD merger rate and the SN Ia rate. For our assumed primary and secondary mass distributions, \( \sim 90\% \) of the mergers are sub-Chandrasekhar, but the total masses are often relatively high—10%–30% of the mergers are \( >1.2 M_{\odot} \), and 25%–50% are \( >1.1 M_{\odot} \). Interestingly, recent theoretical work has explored the possibility of sub-Chandrasekhar CO/CO WD mergers leading to SNe Ia (van Kerkwijk et al. 2010, see also Guillochon et al. 2010; Pakmor et al. 2011). Apart from the consistency between SN Ia rates and the total WD merger rates, sub-Chandrasekhar explosions may have the advantage of producing the correct chemical stratification (Sim et al. 2010), without resorting to the ad hoc delayed detonation mechanism (Khokhlov 1991) needed by Chandrasekhar models. The measured WD merger rate is also important for estimating “foregrounds” for gravitational wave detectors (Nelemans 2009).

Unavoidably, our conclusions depend to some degree on the assumptions made in the analysis. First, all WD samples are flux limited, which could lead to selection effects and unrepresentative values of \( f_{\text{bin}}, \alpha \), or the WD mass distribution. For example, a DD population with a high super-Chandrasekhar merger rate may exist, but remain unobserved. Even so, the DD population we observe, with its high merger rate, does exist, regardless of flux limits. Second, we have modeled the initial WD separation distribution with a power law that is independent of mass. The true post-common-envelope distribution could have some preferred scale correlated with the component masses, which would affect the parameters and merger rates deduced from the \( \Delta V_{\text{max}} \) distribution. We have chosen primary masses based on the distribution observed by Kepler et al. (2007) for SDSS WDs, which are mostly single, and we have drawn secondary masses from a flat mass–ratio distribution. These distributions might be different in DD systems. Different mass distributions would only affect weakly the binary population parameters and the total merger rate, but they would have a strong effect on the super-Chandrasekhar fraction. We might have underestimated \( \Delta V_{\text{max}} \) for some double-lined WD binaries that are unresolved at the SDSS spectral resolution, and this would lead to an underestimated merger rate. Conversely, some of the high-\( \Delta V_{\text{max}} \) systems could conceivably be due to faint M star, rather than WD, companions. However, an M star of low enough mass to go undetected in the SDSS photometry, \( \lesssim 0.15 M_{\odot} \), and with a period of \( \gtrsim 1 \) hr, would only induce a small \( \Delta V_{\text{max}} \) in the primary WD, e.g., 220 or 270 km s\(^{-1} \), for WDs of 0.6 M\(_{\odot}\) and 0.4 M\(_{\odot}\), respectively. Such systems therefore cannot dominate the high-\( \Delta V_{\text{max}} \) tail. At the spectral resolution of SDSS, the combined absorption plus emission line profiles of some WD+M binaries could mimic a large \( \Delta V_{\text{max}} \), but this should not occur identically for several Balmer lines, so these systems would be removed by our vetting procedure. Finally, we have assumed that the velocity errors are normally distributed, with standard deviations quantified by our empirical tests, but there

### Table 1

Local WD Merger Rates and 95% Confidence Limits

| \( \alpha \) | \( f_{\text{bin}} \) | Total Rate \((10^{-13} \text{ mergers yr}^{-1} \text{ M}_{\odot}^{-1})\) | Super-Chandrasekhar Rate \((10^{-13} \text{ mergers yr}^{-1} \text{ M}_{\odot}^{-1})\) |
|---|---|---|---|
| Entire range | 0.014–0.32 | 1.4 (0.16, 7.2) | 0.1 (0.016, 0.4) |
| 1.0 | 0.11–0.24 | 0.3 (0.065, 0.5) | 0.03 (0.017, 0.045) |
| 0.0 | 0.046–0.22 | 1.0 (0.46, 2.2) | 0.08 (0.03, 0.16) |
| −1.0 | 0.021–0.11 | 3.0 (1.0, 6.0) | 0.16 (0.05, 0.3) |
might be some low, non-Gaussian, tails to the error distribution that contaminate the \( \Delta R_{\text{max}} \) distribution with false positives. In an upcoming work, we will improve the purity of our \( \Delta R_{\text{max}} \) distribution with spectroscopic follow-up of a large number of binary candidates, and use this improved distribution to refine our constraints on the Galactic DD population and its merger rate.

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