The merger rate of extremely low mass white dwarf binaries: links to the formation of AM CVn stars and underluminous supernovae

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ABSTRACT
We study a complete, colour-selected sample of double-degenerate binary systems containing extremely low mass (ELM) \( \leq 0.25 \, M_{\odot} \) white dwarfs (WDs). We show, for the first time, that Milky Way disc ELM WDs have a merger rate of approximately \( 4 \times 10^{-5} \, \text{yr}^{-1} \) due to gravitational wave radiation. The merger end product depends on the mass ratio of the binary. The ELM WD systems that undergo stable mass transfer can account for \( \gtrsim 3 \) per cent of AM Canum Venaticorum (AM CVn) stars. More importantly, the ELM WD systems that may detonate merge at a rate comparable to the estimated rate of underluminous supernovae (SNe), rare explosions estimated to produce only \( \sim 0.2 \, M_{\odot} \) worth of ejecta. At least 25 per cent of our ELM WD sample belong to the old thick disc and halo components of the Milky Way. Thus, if merging ELM WD systems are the progenitors of underluminous SNe, transient surveys must find them in both elliptical and spiral galaxies.

Key words: binaries: close – white dwarfs – Galaxy: stellar content.

1 INTRODUCTION
We use the first complete, well-defined sample of extremely low mass (ELM) \( \leq 0.25 \, M_{\odot} \) white dwarfs (WDs; Brown et al. 2010) to calculate the space density and merger rate of these unusual double-degenerate systems. ELM WDs are noteworthy because (1) they comprise \(< 0.2\) per cent of all spectroscopically confirmed WDs (Eisenstein et al. 2006) and (2) the Universe is not old enough to produce ELM WDs through single star evolution. Radial velocity follow-up of the 12 ELM WDs in the Hypervelocity Star Survey (Brown et al. 2005, 2007; Brown, Geller & Kenyon 2009) reveals that they are all binaries with short \((1–14 \, \text{h})\) orbital periods. Remarkably, six of our 12 ELM WDs will merge in less than a Hubble time. A similar merging WD system (J1257 + 5428; Badenes et al. 2009) generated excitement when its companion was thought to be a neutron star (Thompson, Kistler & Stanek 2010). Improved spectroscopy shows that the system contains a pair of WDs (Kulkarni & van Kerkwijk 2010; Marsh et al. 2010), just like the ELM WD systems studied here.

Depending on the stability of mass transfer in the Roche lobe overflow phase, ELM WD binary mergers produce two possible outcomes. ELM WD binaries with mass ratios \( \lesssim 0.2 \) experience stable mass transfer and form AM Canum Venaticorum (AM CVn) systems, a class of ultracompact binaries that consist of a WD accretor and a helium donor star (Nelemans 2005; Warner 1995; Solheim 2010). With their short \(< 1 \, \text{h} \) orbital periods, AM CVn stars are important gravitational wave sources (Hils & Bender 2000; Nelemans, Yungelson & Portegies Zwart 2004). Three proposed formation channels for AM CVn stars involve three different types of donor stars: WDs, helium stars or slightly evolved main-sequence stars (e.g. Podsiadlowski, Han & Rappaport 2003). Distinguishing the dominant formation channel for AM CVn stars is difficult, however, because all three channels lead to the same helium mass-transfer state. Studying the space density and merger rates of progenitors such as our sample of ELM WD binaries places an important constraint on AM CVn formation.

ELM WD binaries with mass ratios \( \gtrsim 0.7 \) experience unstable mass transfer that will result in a merger or possibly an explosion. Whether ELM WD binaries merge or explode, and how they do so, are open theoretical problems. This Letter is focused on observations: we compare the observed merger rate of ELM WD binaries with one possible outcome relevant to current transient surveys, underluminous supernovae (SNe).

Underluminous SNe, such as SN 2005E and SN 2008ha, are rare types of supernova explosions that are 10–100 times less luminous.
than a normal Type Ia SN and have only \(-0.2\, M_\odot\) worth of ejecta. One proposed origin for underluminous SNe is the detonation of a helium layer on a sub-Chandrasekhar mass WD (Nomoto 1982; Woosley, Taam & Weaver 1986). Guillochon et al. (2010) argue that instabilities in the accretion stream can detonate the helium layer. In the ‘Ia’ scenario, a sufficient mass of helium accumulates in the AM CVn mass-transfer phase to ignite and explode (Bildsten et al. 2007; Shen et al. 2010). It is unclear which scenario actually occurs for a merging ELM WD, however, because the physics of the merger process, such as the mass-transfer rates, are poorly constrained.

Observationally, ELM WD merger models can successfully explain the stellar environment, nucleosynthesis products, spectra and light curves of observed underluminous SNe. Half of the known calcium-rich underluminous Type Ib/c SNe are observed in old-population environments (Perets et al. 2010): SN 2005E is located 11 kpc (projected) above the disc of its host galaxy, while SN 2000ds, SN 2005cz and SN 2007ke are located in elliptical galaxies. These objects cannot be explained by the core collapse of massive stars, but are easily explained by merging WDs. A low ejecta mass of calcium-rich material is a natural result of burning helium-rich material on a WD (e.g. Woosley et al. 1986). The rapid light curve decay of SN 2010X, for example, can be explained with the Ia model (Kasliwal et al. 2010). Waldman et al. (2010) are able to model both the observed spectrum and the light curve of SN 2005E with the detonation of a 0.2 M_\odot He-layer on a 0.45 M_\odot WD. Half of our merging ELM WD systems have similar mass ratios. Measuring the rate of our ELM WD mergers thus provides an additional observational constraint on links to underluminous SNe.

Our Letter is organized as follows. In Section 2 we discuss the ELM WD sample. In Section 3 we derive the space density of ELM WDs. In Section 4 we estimate the merger rate of ELM WDs in the Milky Way, $4 \times 10^{-5}$ yr\(^{-1}\). This first estimate suffers from factors of 2 uncertainties; however it demonstrates that merging ELM WD binaries are viable progenitors of both AM CVn stars and underluminous SNe.

### 2 SAMPLE

Our sample of 12 \(\leq 0.25\, M_\odot\) ELM WDs comes from a radial velocity survey of stars selected uniformly by magnitude 15 \(<\, g\, <\, 20.5\) and colour. The approximate colour limits are 0.1 \(<\, (u - g)_0\, <\, 0.9\), \(-0.45\, <\, (g - r)_0\, <\, -0.2\) and \(-0.5\, <\, (r - i)_0\, <\, 0\) (Brown et al. 2007, 2009) provide the exact prescription. The colour selection was designed to find halo stars with late-B type colours. However, 15 per cent of the survey stars are WDs, 12 of which have \(\leq 0.25\, M_\odot\). Follow-up spectroscopy reveals that 11 of the 12 ELM WDs are binaries with 1–14 h orbital periods (Brown et al. 2010). The single non-variable ELM WD is consistent with the number of pole-on systems expected in a sample of 12 non-kinematically selected targets. Thus we assume that all of the ELM WDs are binaries, and that the orbital parameters of the 11 ELM WDs fairly sample the underlying distribution.

We estimate luminosities and distances for our ELM WDs using the updated Panei et al. (2007) evolutionary tracks for He-core WDs. The luminosity estimates encompass +8.0 \(<\, L_\odot\, <\, +9.9\) and correspond to heliocentric distances of 0.3 kpc \(<\, d\, <\, 3.1\) kpc (Brown et al. 2010). The sample covers a 9800 deg\(^2\) region of the Sloan Digital Sky Survey (SDSS) Data Release 7 imaging footprint and is currently 90 per cent complete in this area. Thus we assume that there are 10 per cent more ELM WDs in our colour–magnitude range when estimating the ELM WD space density.

### 3 DENSITY

The simplest approach to estimating the space density of ELM WDs is to divide the observed number of ELM WDs by the survey volume. This simple approach provides a robust lower limit, but only for ELM WDs sampled by our survey. ELM WDs are missing from our sample (1) because they cool and (2) because they merge. Thus we need to correct our survey for ELM WDs that have cooled outside of our colour range and that have merged. Our survey samples ELM WDs that formed in the last 1 Gyr, thus that is what we consider here. For a constant formation rate, we will show that older ELM WDs contribute only a few per cent to the present merger rate. Because the contribution of these delayed mergers is much smaller than our uncertainties, the unknown formation history of ELM WDs does not significantly affect our conclusions. In this section we estimate the present number of ELM WDs that exist in the Galaxy. In the next section we estimate the ELM WD merger rate.

#### 3.1 Cooling time correction

Once formed, WDs cool and become redder and fainter with time. The rate of cooling depends sensitively on WD mass. Updated Panei et al. (2007) evolutionary tracks for He-core WDs show that 0.17 M_\odot WDs spend \(\approx\) 1 Gyr cooling through our colour (effective temperature) range with approximately constant luminosity, $M_\odot \approx +8.0$. On the other hand, 0.2–0.25 M_\odot WDs spend only $\approx\, 0.25$ Gyr cooling through our colour range and with declining luminosities, $M_\odot$ dropping from +8 to +10. The difference between the 0.17 M_\odot and 0.2–0.25 M_\odot He-core WDs is explained by the thermonuclear flash threshold in the hydrogen shell burning phase (Panei et al. 2007). We note that the tracks have the WDs spending 10\(^{-7}\)–10\(^{\text{yr}}\) at hotter temperatures, or 1–10 per cent of the time spent in our colour range. Serenelli et al. (2001) tracks yield similar numbers.

Clearly, our colour selection samples ELM WDs that have formed within the last 1 Gyr. In addition, the relation between mass and cooling time skews the number of ELM WDs of different mass that we observe. Each observed WD implies the formation of (1 Gyr)/$t_{\odot}$ objects in the last Gyr, where $t_{\odot}$ is the time spent cooling through our colour range in Gyr. We take $t_{\odot}$ = 1 Gyr for the eight $\geq 0.17$ M_\odot WDs in our sample, and $t_{\odot} = 0.25$ Gyr for the four 0.2–0.25 M_\odot WDs (Serenelli et al. 2001; Panei et al. 2007). This correction factor links the observed sample of ELM WDs to the total number that have formed in the last Gyr that presently exist in our survey volume.

The relation between luminosity and temperature also affects the volume over which we observe different mass ELM WDs. This is accounted for in our $1/V_{\text{max}}$ density estimate below, with the implicit assumption that the population of ELM WDs is the same in all volumes.

#### 3.2 Merger time correction

ELM WDs are missing from our sample because they merge. The merger time due to angular momentum loss from gravitational wave radiation is $\tau = (M_1 + M_2)^{1/3} P^{8/3} \times 10^{\text{yr}}$, where the masses are in M_\odot and the period $P$ is in hours (Landau & Lifshitz 1958).

Both the mass ratio $M_1/M_2$ and the merger time $\tau$ depend on the mass of the unseen companion and the unknown orbital inclination ($M_2 \sin i$). An edge-on orbit with $i = 90^\circ$ gives the minimum possible
Next, we calculate the local space density of ELM WDs using the thick disc fraction adopted here is low compared to more recent
is the radial distance along the Galactic plane in kpc. Although
J0818+3536 and J1422+3536, which have systemic radial velocities of −202 and −193 km s⁻¹, respectively. Kilic et al. (2010)
argue that J1053+5200 is also a halo object based on its proper motion. Reliable proper motions are unavailable for the majority of
our ELM WDs, however. We choose to make a self-consistent cut on systemic radial velocity. The inclusion of a spurious halo object in our disc sample would cause us to overestimate the local space density by ±10 per cent.

The volume sampled by our survey varies with both radial distance $R$ and vertical distance $Z$. We compute $V_{\text{max}}$ by starting with the SDSS stripe definitions, converting them to Galactic coordinates and then integrating the volume over our $15 < g < 20.5$ apparent magnitude range for each WD absolute magnitude.

Given the assumed disc model, the completeness-corrected local space density of disc ELM WDs is $\rho_0 = 40$ kpc⁻³. The error is dominated by the factor of 2 uncertainty in our correction factors. Integrating the disc model over $0 < R < 25$ kpc and $0 < |Z| < 10$ kpc, we estimate that $5 \times 10^5$ ELM WDs formed in the Milky Way disc in the last Gyr.

### 4 MERGER RATES

The merger times are encoded in the orbital period distribution of the ELM WDs. In principle, we can calculate the initial period distribution required to produce the observed period distribution under the assumption of gravitational wave radiation energy loss. Given our small number statistics, this approach is fraught with uncertainty.

The approach we take is to consider the observed sample of ELM WDs a snapshot in time of the whole population. We use the observed orbital periods as a proxy for the underlying period distribution. For reference, Fig. 1 plots the mass ratio $M_1/M_2$ and merger time $\tau$ for our sample of ELM WDs, excluding the probable pole-on system. Filled squares in Fig. 1 are the most probable

| ID           | $M_1$ (M⊙) | $t_{\text{obs}}$ (Gyr) | $M_1/M_2$ | $\tau$ (Gyr) | $N_{\text{cor}}$ |
|--------------|-------------|------------------------|-----------|--------------|-----------------|
| J0755+4906   | 0.17        | 1                      | 0.151     | 0.17         | 5.8             |
| J0818+3536   | 0.17        | 1                      | 0.513     | 7.31         | 1.0             |
| J0917+4638   | 0.17        | 1                      | 0.489     | 30.3         | 1.0             |
| J0923+3028   | 0.23        | 0.25                   | 0.528     | 0.11         | 9.4             |
| J1053+5200   | 0.20        | 0.25                   | 0.614     | 0.13         | 7.6             |
| J1233+1602   | 0.17        | 1                      | 0.142     | 1.69         | 1.0             |
| J1422+4352   | 0.17        | 1                      | 0.309     | 34.7         | 1.0             |
| J1439+1002   | 0.18        | 0.25                   | 0.292     | 44.1         | 1.0             |
| J1448+1342   | 0.25        | 0.25                   | 1.9       | 4.0          |                 |
| J1512+2615   | 0.20        | 0.25                   | 0.555     | 140.3        | 4.0             |
| J1630+2712   | 0.17        | 1                      | 0.242     | 12.5         | 1.0             |
| J2119-0018   | 0.17        | 1                      | 0.163     | 0.42         | 2.4             |

$k = 60°$.

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Figure 1. Gravitational wave radiation merger time versus mass ratio for the sample of ELM WDs, excluding the probable pole-on system. $M_1$ is the observed ELM WD and $M_2$ is the unseen binary companion. Filled squares show the most probable values for $i = 60°$, and lines indicate the possible range of values over the 90th percentile range $25° < i < 90°$. ELM WD binaries with mass ratios below the dashed line will experience stable mass transfer and become AM CVn stars; binaries above the dashed line will experience unstable mass transfer and may explode as underluminous SNe.

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values for $i = 60^\circ$, and lines show the possible values over the 90th percentile range $25^\circ < i < 90^\circ$.

Four of the ELM WD systems in our sample have merger times less than 1 Gyr. The short merger times of these systems suggest that they represent 70 per cent of the ELM WD systems that formed in the last Gyr, as determined by the correction factors calculated above. Combining the above numbers, the merger rate of ELM WDs in the Galaxy is approximately $0.7 \times 10^5/1 \text{ Gyr} \simeq 4 \times 10^{-5} \text{ yr}^{-1}$. We get a similar number if we divide the number of ELM WDs by the harmonic mean of the observed merger times.

A $4 \times 10^{-5} \text{ yr}^{-1}$ merger rate is likely an underestimate for a few reasons. First, some ELM WD systems formed long ago and are now merging. In our corrected sample, 5 per cent of ELM WDs have mergers times of 1–8 Gyr. If the formation rate of ELM WD systems was constant over the 8 Gyr age of the disc (Leggett, Ruiz & Bergeron 1998), then the contribution of delayed mergers is approximately $10^{-6} \text{ yr}^{-1}$. The contribution increases if we account for the increased star formation rate at early time, but deceases if we account for the delay to form ELM WD systems. Fortunately, the contribution of delayed mergers is so small that knowing the detailed formation history of ELM WDs is unnecessary; the ELM WD merger rate is dominated by short merger times.

Secondly, our observations may be missing ELM WD systems with merger times $< 10^8 \text{ yr}$. For a 1 Gyr lifetime in our survey region, we expect ELM WDs with merger times $< 10^8 \text{ yr}$ to contribute $< 10$ per cent to our sample. Objects with $< 10^8 \text{ yr}$ merger times have $< 1$ h periods, periods in the realm of observed AM CVn systems. The contribution of ELM WD systems formed with $< 1$ h periods may be better estimated from AM CVn rates. A single $10^7 \text{ yr}$ merger would double our estimated merger rate.

Finally, accounting for the halo and bulge components of the Milky Way would also increase the merger rate estimate: star count models suggest that the stellar halo contains 10 per cent of the stellar disc mass (Jurić et al. 2008), and the bulge a similar amount (Widrow & Dubinski 2005). All of these corrections act to increase the merger rate, thus our estimate is likely a lower limit to the true ELM WD merger rate.

### 4.1 Comparison with AM CVn rates

The ELM WD systems with mass ratios $< 0.25$ will likely become stable-mass-transfer AM CVn systems. Based on the mass functions, the companions to these objects must have $> 0.5 \text{ M}_\odot$ and thus are probably normal C/O core WDs. Although the stable-mass-transfer ELM WDs comprise 50 per cent of the observed merger systems (two of four with $r < 1$ Gyr, or three of six with $r < 8$ Gyr), the correction factors suggest that they account for 33 per cent of the overall ELM WD merger rate. The different percentages illustrate the small number statistics involved. Thus we consider the range of rates, $(1–2) \times 10^{-5} \text{ yr}^{-1}$, with the reminder that our merger rates are likely underestimates.

Roelofs et al. (2007a) and Roelofs, Nelemans & Groot (2007b) make an order-of-magnitude estimate of the disc AM CVn birth rate of $5 \times 10^{-4} \text{ yr}^{-1}$ based on samples containing five and six AM CVn stars. Comparing with the stable-mass-transfer ELM WDs in our sample suggests that ELM WDs contribute at least 2–4 per cent of the AM CVn population. Although this is an order-of-magnitude comparison, our observations show for the first time that merging ELM WD systems are a likely source of AM CVn stars.

### 4.2 Comparison with underluminous SNe rates

The ELM WD systems with mass ratios of $\geq 0.55$ will likely become unstable-mass-transfer systems. These systems include the two shortest merger time objects; the correction factors imply that unstable-mass-transfer ELM WDs account for 67 per cent of the ELM WD merger rate. Given the observed mass ratios, there is a 40 per cent probability that the ELM WD companions are C/O WDs ($M \geq 0.45 \text{ M}_\odot$). That means 40 per cent of the unstable-mass-transfer systems may lead to surface He detonation on a C/O WD (e.g. Guillochon et al. 2010). Stable-mass-transfer systems may also detonate as ‘Ia’ SNe (e.g. Bildsten et al. 2007). Thus the rate of ELM WD mergers that may become underluminous SNe is $(2–3) \times 10^{-5} \text{ yr}^{-1}$, with the reminder that these rates are likely underestimates.

For comparison, the Type Ia SNe rate of the Milky Way is $5 \times 10^{-3} \text{ yr}^{-1}$ (Li et al. 2010). ELM WDs are an unlikely source of Type Ia SNe because of their low system mass. The relevant comparison is with underluminous SNe.

Foley et al. (2009) estimate that a SN 2008ha-type explosion is observable to a distance of 40 Mpc, a volume that has had 60 known SNe Type Ia in the past 10 yr. Thus, based on one object, Foley et al. (2009) estimate that the underluminous SNe rate is $\sim 2$ per cent of the Type Ia rate, or $\sim 1 \times 10^{-4} \text{ yr}^{-1}$. This is a few times larger than the rate of ELM WD mergers that may become underluminous SNe.

We close by noting that at least two of our ELM WDs are halo objects and an equal or greater number are probably thick-disc objects. The halo and thick disc are old stellar populations. If ELM WDs are the progenitors of underluminous SNe, underluminous SNe must be found in both elliptical and spiral galaxies.

## 5 CONCLUSIONS

We study the space density and merger rate of double-degenerate binary systems containing $\leq 0.25 \text{ M}_\odot$ ELM WDs. This work is motivated by the first complete, well-defined sample of 12 ELM WDs fortuitously targeted by the Hypervelocity Star Survey (Brown et al. 2005, 2007, 2009). The ELM WDs are all consistent with being short-period binaries (Brown et al. 2010). Remarkably, six of the 11 systems with good period determinations will merge in less than a Hubble time due to gravitational wave radiation.

The merger rate of disc ELM WD binaries in the Milky Way is approximately $4 \times 10^{-4} \text{ yr}^{-1}$. Although the uncertainty in this estimate is at least a factor of a few, the observations establish that merging ELM WD binaries are viable progenitors for several interesting phenomena. ELM WD systems that undergo stable mass transfer contribute at least 2–4 per cent of the observed AM CVn population. More importantly, ELM WD systems that may detonate merge at a rate comparable to the observed rate of underluminous SNe. Other possible outcomes include mergers that form extreme helium stars or helium-rich sdO stars.

Further progress requires advances in both theory and observation. Understanding how ELM WD binaries merge and ignite is an open problem. Greater numbers of AM CVn stars must be found to better constrain their properties (Rau et al. 2010). New imaging surveys such as the Palomar Transient Factory, the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), Skymapper and eventually the Large Synoptic Survey Telescope will discover large numbers of unusual transients such as underluminous SNe.

Our goal is to use observations to investigate links between double-degenerate mergers and unusual transients. In the future, obtaining a larger sample of 30 ELM WDs will improve the
uncertainty in our ELM WD space density and merger rate estimates by a factor of 2. We anticipate this is the first step in our ELM Survey towards a greater understanding of merging ELM WD systems.

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