Massive Double White Dwarfs and the AM CVn Birthrate

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ABSTRACT

We present Chandra and Swift X-ray observations of four extremely low-mass (ELM) white dwarfs with massive companions. We place stringent limits on X-ray emission from all four systems, indicating that neutron star companions are extremely unlikely and that the companions are almost certainly white dwarfs. Given the observed orbital periods and radial velocity amplitudes, the total masses of these binaries are greater than 1.02 to 1.39 M\textsubscript{☉}. The extreme mass ratios between the two components make it unlikely that these binary white dwarfs will merge and explode as Type Ia or underluminous supernovae. Instead, they will likely go through stable mass transfer through an accretion disk and turn into interacting AM CVn. Along with three previously known systems, we identify two of our targets, J0811 and J2132, as systems that will definitely undergo stable mass transfer. In addition, we use the binary white dwarf sample from the ELM Survey to constrain the inspiral rate of systems with extreme mass ratios. This rate, $1.7 \times 10^{-4}$ yr\textsuperscript{-1}, is consistent with the AM CVn space density estimated from the Sloan Digital Sky Survey. Hence, stable mass transfer double white dwarf progenitors can account for the entire AM CVn population in the Galaxy.

Key words: binaries: close — white dwarfs — stars: individual (SDSS J075519.47+480034.0, SDSS J081133.56+022556.7, SDSS J144342.74+150938.6, SDSS J213228.36+075428.2)

1 INTRODUCTION

Short period binary white dwarfs will lose angular momentum through gravitational wave radiation and start mass transfer. The shortest period detached double white dwarf system currently known, J0651 \textsuperscript{[Brown et al. 2011; Hermes et al. 2012]}, will start mass transfer in less than 1 Myr. What happens next depends on the stability of mass transfer.

For roughly equal mass binaries, the two stars will merge and form a more massive white dwarf (for CO+CO white dwarfs), an R Cor Bor star (for CO+He white dwarf mergers), or a single subdwarf (for He+He white dwarfs). Depending on the total mass of the system, the mergers can also lead to underluminous or normal Type Ia supernovae in both CO+CO and CO+He white dwarf mergers \textsuperscript{[Webbink 1984, Iben & Tutukov 1984]}. The latter systems may go through a double detonation, in which the detonation of the underlying CO core white dwarf (e.g., \textsuperscript{[Shen & Bildsten 2011]})

For binaries with extreme mass ratios, the mass transfer will be stable \textsuperscript{[Marsh et al. 2004]}, leading to the formation of AM CVn binaries. AM CVn have orbital periods of 5-65 min and involve an accreting white dwarf and a He-rich donor star. Given the stability of the mass transfer, the orbit slowly expands to accommodate the increasing size of the degenerate donor, the mass transfer rate decreases, and the binary evolves into a massive white dwarf with a planetary size companion. Despite large scale efforts to find AM CVn \textsuperscript{[Carter et al. 2013]}, there are only 52 systems currently known. Hence, AM CVn represent the end product of a rare and fine-tuned evolution in binary systems \textsuperscript{[Solheim 2010]}.

There are three formation channels for AM CVn with three different donor stars; low-mass white dwarfs, helium stars, or evolved main-sequence stars. The population synthesis models predict that the double white dwarf channel
dominates the AM CVn formation (Nelemans et al. 2001; Nissanke et al. 2012). However, it is difficult to distinguish between the different formation channels based on the observed AM CVn population, since all three channels essentially lead to very low-mass degenerate He-rich donors. Nelemans et al. (2010) demonstrate that N/C abundance ratios significantly differ between the He-white dwarf and He star donors, and use this to identify He white dwarf donors in three AM CVn systems. Breedt et al. (2012) present the first compelling evidence for an AM CVn progenitor with an evolved main-sequence donor. They constrain the orbital period of CSS1122-1110, a cataclysmic variable with unusually strong He lines, to 65.2 min and use the superhump period excess to infer a mass ratio of 0.017. Kennedy et al. (2013) identify three other systems with evolved main-sequence donors as potential progenitors of AM CVn, though the mass ratios are not as extreme as CSS1122-1110. Observationally, it remains unclear what is the dominant formation channel for AM CVn systems.

The ELM Survey (Brown et al. 2016a, and references therein) has found 76 short period double white dwarfs so far, including several systems with extreme mass ratios. Kilic et al. (2013) identify two of these systems, J0751-0141 and J1741+6826, as the first confirmed AM CVn progenitors from the double white dwarf channel. Here we present follow-up observations of four more ELM white dwarfs with massive companions, and demonstrate that two of these targets will have stable mass transfer. In addition, we estimate the merger rate of ELM white dwarfs with massive companions. We present our target selection and observations in §2, and discuss the nature of the companions and the inspiral rate of extreme mass ratio binaries in the ELM Survey in §3. We conclude in §4.

2 OBSERVATIONS AND RESULTS

2.1 Target Selection and Motivation for X-ray Observations

ELM white dwarfs are single-lined spectroscopic binaries in which the ELM white dwarf dominates the light of the system. We define \( M_1 \) as the visible low mass white dwarf and \( M_2 \) as its unseen companion. We measure orbital period and radial velocity semi-amplitude, and derive \( M_1 \) by comparing our spectroscopic log \( g \) and \( T_{\text{eff}} \) measurements to evolutionary tracks for low-mass He-core white dwarfs (Althaus et al. 2013). In the absence of information about inclination, such as eclipses, the observations provide a lower limit on \( M_2 \).

Figure 1 shows the minimum total system mass versus the orbital period for the 76 binaries discovered in the ELM Survey. Nine of these targets have previous Chandra or XMM-Newton observations that rule out neutron star companions, and an additional six targets have radio data that rule out milli-second pulsars. To search for neutron star companions, we selected four of the most massive binary systems known from an earlier version of the ELM Survey sample for follow-up X-ray observations. Table 1 presents the physical parameters of these four systems, including the minimum companion masses (Gianninas et al. 2015).

Given the short orbital periods \( (P \leq 1 \text{ d}) \) and very low masses for the observed white dwarfs (requiring evolutionary stripping), neutron star companions to our targets would be spun up to millisecond periods. Such millisecond pulsars can be detected in the radio, but the radio pulsar beam may miss our line of sight. Instead, X-ray observations enable us to observe the blackbody emission from \( > 75\% \) of the neutron star surface (Heinke et al. 2005) and Bogdanov et al. (2006) detected all 15 radio millisecond pulsars in unconfused regions of 47 Tuc in X-rays, with \( L_X (0.5 - 6 \text{ keV}) \geq 2 \times 10^{30} \text{ erg s}^{-1} \). Continued measurements of X-ray fluxes and distances of radio millisecond pulsars have revealed a few systems with lower X-ray luminosities (e.g., Pavlov et al. 2007; Kargaltsev et al. 2012; Forestell et al. 2014; Spiewak et al. 2015). Of 52 millisecond pulsars in the list of Forestell et al. (2014), only four have X-ray luminosities below \( 10^{30} \text{ erg s}^{-1} \). Hence, deep X-ray observations that place an \( L_X \) limit at or below \( 10^{30} \text{ erg s}^{-1} \) can confirm or provide strong evidence against neutron star companions to our targets.

2.2 No Neutron Star Companions

We observed three targets, J0811, J1443, and J2132, with Chandra’s ACIS-S detector in Very Faint mode, for 32.6, 1.3, and 11.6 ks, respectively. These observations were performed between 2014 Dec and 2015 Feb. We reprocessed the raw Chandra data using CIAO 4.5. Inspection of the 0.3-7 keV

\footnotetext{1 Desvignes et al. (2016) provide a parallax distance for PSR J1024-0719 of 1083 ± 28 \text{ pc}, indicating \( L_X = 2.8 \times 10^{30} \text{ erg s}^{-1} \).}
images revealed only 1 photon within $1''$ of the position of J0811, and zero photons for the other two white dwarfs.

We also obtained 1.1 ks Swift XRT observations of J0755 on UT 2014 March 10. Unfortunately, J0755 landed on a bad column in the XRT, which reduced the effective exposure time by a factor of three. We obtained an additional 1.0 ks Swift observation of the same target on UT 2016 Feb 22. We used a 20'' region for X-ray extraction, which encloses 80% of the Swift/XRT point spread function (Moretti et al. 2004). We find zero photons within this extraction region.

We used the COLDEN tool to interpolate the Dickey & Lockman (1990) HI survey, and estimate $N_H$ values for each target. We also use the PIMMS tool to compute the unabsorbed 0.3-8 keV flux for a 134 eV blackbody (appropriate for the faintest 47 Tuc millisecond pulsar, 47 Tuc T, Bogdanov et al. 2006). We calculate 95% confidence upper limits (4.7 counts for J0811 and 3 counts for the other three stars, Gehrels 1986), to the 0.3-8 keV confidence upper limits for each target. We also use the $L_X$ upper limits for each target.

The 95% confidence upper $L_X$ limits for all four targets are a factor of two or more below the luminosity of a millisecond pulsar in 47 Tuc, using the blackbody fluxes reported in Bogdanov et al. (2006) and a 4.5 kpc distance (Harris 1996, 2010 revision). We conclude that our X-ray observations provide strong evidence against neutron star companions for all four targets.

Radio and optical follow-up observations of pulsars indicate that He white dwarf companions are common. There are more than 100 pulsar + He white dwarf systems known in the Australia Telescope National Facility Pulsar Catalogue (2016 version, Manchester et al. 2005). However, the reverse approach, the search for milli-second pulsar companions through X-ray or radio follow-up of ELM white dwarfs, has so far resulted in no new pulsar discoveries (van Leeuwen et al. 2007; Agieros et al. 2009; Kilic et al. 2011, 2012, 2014, and this study). Based on a statistical analysis of the companion mass distribution to ELM white dwarfs, Andrews et al. (2014) find a neutron star companion fraction of <16% (see also Boffin 2014; Brown et al. 2016a). Hence, follow-up X-ray or radio observations of a larger sample of ELM white dwarfs are necessary to discover the first pulsar through its white dwarf companion.

2.3 Optical Photometry

A significant number of short period binary white dwarfs display photometric variations due to tidal distortions, the relativistic beaming effect, or eclipses (Hermes et al. 2014). The photometric variations are a function of the white dwarf radii, orbital separation, and orbital inclination. For example, the two previously confirmed AM CVn progenitors, J0751 and J1741 display 3.2% and 1.3% ellipsoidal variations. The amplitude of the ellipsoidal effect is roughly $\Delta f_{ell} = \left( \frac{m_2/m_1}{r_1/a} \right)^2$, where $a$ is the orbital semi-major axis and $r_1$ is the radius of the primary (Zucker et al. 2007; Shporer et al. 2011). The four targets presented in Table 1 have orbital periods and separations significantly larger than J0751 and J1741. Hence, the expected amplitude of the ellipsoidal effect is smaller than 0.05% for all four targets.

Figure 2 displays the unfiltered optical light curves for three of our targets from the Catalina Sky Survey (Drake et al. 2000). The remaining target, J0811, has a galaxy within 6.6'' and its light curve is not available in the Catalina Sky Survey Data Release 2. J0811 was not observed by the Palomar Transient Factory (PTF, Rau et al. 2009). Hence, we do not have any photometric constraints on this binary. The Catalina data for J0755, J1143, and J2132 are relatively noisy, and a Fourier analysis does not reveal any significant periodicities for the latter two systems. The right panels show the Catalina and $R$-band PTF light curves for these two stars, folded on the best-fit period from the radial velocity data. There are no significant photometric variations at the orbital period for J1143 and J2132.

The Catalina data for J0755 show large scatter that is consistent with long term variations of order $P > 600$ d. However, J0755 is within 18'' of a $g = 13.88$ mag star, and it is not clear if the Catalina photometry is affected by this nearby source. We obtained follow-up $V$-band optical photometry of J0755 over 20.7 h between UT 2016 Feb 28 and Mar 3 using Celestron 28-cm and 35-cm Schmidt-Cassegrain telescopes at the Acton Sky Portal private observatory. The top right panel in Fig. 2 displays the phase-folded light curve for J0755. There is no evidence of photometric variations at the orbital period for J0755 in our data, as well as the PTF data that covers MJD 55081-57468 (T. Kupfer 2016, priv. comm.). Given the precision of our light curves and the relatively small amplitudes of the predicted ellipsoidal variations and the Doppler beaming effect, the absence of optical photometric variations in J0755, as well as J1443 and J2132, is not surprising. Unfortunately, the absence of photometric variations leaves us with no additional information on the binaries.

3 DISCUSSION

3.1 Four Massive Double White Dwarfs

Our Chandra and Swift X-ray observations demonstrate that all four of our low-mass white dwarf targets almost certainly have massive white dwarf companions. J0811 is the most extreme system in our sample with a 0.18 $M_\odot$ companion.

Table 1. Physical parameters of our targets.

| SDSS          | $T_{\text{eff}}$ (K) | $\log g$ (cm s$^{-2}$) | $M_1$ ($M_\odot$) | $R_1$ ($R_\odot$) | Period (days) | $M_{2,\text{min}}$ ($M_\odot$) | $a$ ($R_\odot$) |
|---------------|----------------------|------------------------|-------------------|-------------------|---------------|------------------------------|----------------|
| J075519.47+480034.0 | 19530 ± 300          | 7.42 ± 0.05            | 0.41              | 0.0207            | 0.54627       | 0.89                         | 3.07           |
| J081133.56+022556.7 | 13540 ± 200          | 5.67 ± 0.05            | 0.18              | 0.1035            | 0.82194       | 1.21                         | 4.12           |
| J144324.74+150938.6 | 8970 ± 130           | 6.44 ± 0.06            | 0.18              | 0.0424            | 0.19053       | 0.84                         | 1.40           |
| J213228.36+075428.2 | 13790 ± 200          | 6.02 ± 0.04            | 0.18              | 0.0681            | 0.25056       | 0.96                         | 1.75           |
Table 2. The X-ray limits on our targets.

| Name  | ObsID   | Dist (kpc) | \(N_H\) (cm\(^{-2}\)) | Exp (ks) | Count rate (cts s\(^{-1}\)) | \(L_X\) (ergs s\(^{-1}\)) |
|-------|---------|------------|-----------------|---------|------------------|-----------------|
| J0755 | 33183002| 0.17       | \(4.8 \times 10^{20}\) | 1.0     | < 3.8 \times 10^{-3} | < 5.6 \times 10^{29} |
| J0811 | 16687   | 2.20       | \(3.5 \times 10^{20}\) | 32.6    | < 1.4 \times 10^{-4} | < 1.1 \times 10^{30} |
| J1443 | 16685   | 0.54       | \(1.5 \times 10^{20}\) | 1.3     | < 2.3 \times 10^{-3} | < 1.0 \times 10^{30} |
| J2132 | 16686   | 1.09       | \(4.4 \times 10^{20}\) | 11.6    | < 2.6 \times 10^{-4} | < 5.4 \times 10^{29} |

Figure 2. Left Panels: Catalina Sky Survey light curves for three of our targets. Right Panels: Phase folded light curves (using the orbital period measured from the radial velocity data) for the same three targets based on the Acton Sky Portal (top), Catalina Sky Survey (middle), and Palomar Transient Factory (bottom) data.

A white dwarf and a \(\geq 1.21 M_\odot\) white dwarf companion. However, the merger time due to gravitational wave radiation is longer than a Hubble time. J2132 is the second most massive system, with a 0.18 \(M_\odot\) white dwarf and a \(\geq 0.96 M_\odot\) white dwarf companion. Given the mass ratio of \(q < 0.2\), J2132 will start stable mass transfer in 5.5-7.2 Gyr and turn into an AM CVn.

Figure 3 shows the mass transfer stability limits from Marsh et al. (2004). Binaries with a mass ratio of \(q > \frac{2}{3}\) are expected to have unstable mass transfer and merge. The eclipsing, short period double white dwarfs J1152+0248 (Hallakoun et al. 2016), CSS 41177 (Parsons et al. 2011; Bours et al. 2014), and the double lined binary WD 1242-105 (Debes et al. 2015) are excellent examples of systems in this region. Objects with mass ratios below the solid line will have stable mass transfer, which leads to AM CVn systems instead of mergers.

Along with the previously identified AM CVn progenitors J0751, J1741 (Kilic et al. 2014) and J1257+5428 (Kulkarni & van Kerkwijk 2014; Marsh et al. 2014; Bours et al. 2013), J0811 and J2132 are clearly in the stable mass transfer region (see also Gianninas et al. 2015). Out of these five systems, all but J0811 have merger times shorter than a Hubble time. Hence, there are now four confirmed double white dwarf progenitors of AM CVn.

In addition to these four systems, there are a number of other ELM white dwarfs with unknown inclinations that are likely to have extreme mass ratios. For example, J1443 has a mass ratio of \(q \leq 0.21\) (Fig. 3), which places it in the intermediate region where the stability of mass transfer depends on the synchronization timescale (spin-orbit coupling) of the binary. Assuming that the orbital inclination is distributed randomly in \(\sin i\) within the allowed observational constraints, there is a 46\% chance that J1443 is in the disk accretion region.

3.2 AM CVn Birthrate

Brown et al. (2016a,b) define a clean sample of 60 binary systems from the ELM Survey, which is 60\% complete in a well defined color and magnitude range. They identify 63\% of their sample as disk objects, and use standard Galactic stellar density models to estimate the ELM white dwarf local space density. Using the stellar density model of Nelemans et al. (2001), the merger rate of disk ELM white dwarf binaries in the Milky Way is \(5 \times 10^{-3}\) yr\(^{-1}\), with a
Mass transfer stability for double white dwarfs (Marsh et al. 2004). Disk accretion occurs in the region below the solid line. J0811 and J2132 are clearly in this parameter range. Eclipsing double white dwarf systems and the double-lined binary J1257+5428 (error bars), and other ELM white dwarf binaries with X-ray data (triangles) are also shown.

A remaining question is whether the inspiral rate of the extreme mass ratio systems in the ELM Survey is consistent with the AM CVn formation rate. We perform Monte Carlo simulations of the clean, disk ELM white dwarf binary sample to estimate the probability that each system has a mass ratio that puts it below the stability limit of Marsh et al. (2004) for disk accretion. Since the ELM Survey binaries were selected based on color, the distribution of inclination angles should be random. We include the constraints on inclination for eclipsing systems, and the binaries with X-ray data. The allowed inclinations map to an allowed distribution of $M_2$ for each binary.

Every ELM white dwarf binary has a likelihood of having mass ratios that fall in the stable mass transfer region of parameter space, however not every binary will merge within a Hubble time. We estimate the underlying merger rate by taking the observed distribution of merger times and assuming that ELM white dwarf binaries form at a constant rate over the past Gyr, the approximate time span that ELM white dwarfs are detectable in the ELM Survey color selection.

The inspiral rate for the subset of binaries with extreme mass ratios (that would lead to stable disk accretion) is a factor of 30 lower than the total ELM white dwarf binary merger rate. This is due to factors of 10 longer gravitational wave merger times for the extreme mass ratio systems in our sample, and factors of 3 fewer stars in the stable mass transfer region. Hence, we estimate that the formation rate of stable mass transfer systems from binary ELM white dwarfs is $1.7 \times 10^{-4}$ yr$^{-1}$. This is remarkably similar to the AM CVn formation rate found by Carter et al. (2013). Note that both rates are uncertain by 60-80%. Nevertheless, the extreme mass ratio double white dwarf systems found in the ELM Survey can explain a significant fraction, and perhaps the entire population, of AM CVn found in the Galaxy.

4 CONCLUSIONS

We provide strong evidence against neutron star companions in four ELM white dwarfs with massive companions. J0755 and J0811 are the most massive binary white dwarfs identified in the ELM Survey, with total binary masses of $M \geq 1.3 M_\odot$ and $M \geq 1.39 M_\odot$, respectively. However, both J0755 and J0811 have orbital periods longer than half a day. Hence, they will not interact within a Hubble time. The remaining two stars, J1443 and J2132, have binary mass ratios of $q < 0.21$, and they have short enough orbital periods to start mass transfer in several Gyr. J2132 is clearly in the stable mass transfer range in Figure 3. Hence, there are now four confirmed double white dwarf progenitors of AM CVn: J0751, J1741 (Kilic et al. 2014), J1257+5428 (Bours et al. 2013), and J2132.

More importantly, we take the entire sample of ELM white dwarf binaries, consider the distribution of mass ratios for each system, and derive the inspiral rate for the subset that satisfy the Marsh et al. (2004) stability criterion for disk accretion. This rate is essentially identical to the AM CVn formation rate from Carter et al. (2013); there are sufficient numbers of double white dwarf progenitors of AM CVn to account for the entire population of AM CVn in the Galaxy.

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