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# Found: the progenitors of AM CVn and supernovae .Ia

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## ABSTRACT

We present optical and X-ray observations of two tidally distorted, extremely low-mass white dwarfs (WDs) with massive companions. There is no evidence of neutron stars in our *Chandra* and *XMM* observations of these objects. SDSS J075141.18−014120.9 (J0751) is an eclipsing double WD binary containing a 0.19 $M_{\odot}$ WD with a 0.97 $M_{\odot}$ companion in a 1.9 h orbit. J0751 becomes the fifth eclipsing double WD system currently known. SDSS J174140.49+652638.7 (J1741) is another binary containing a 0.17 $M_{\odot}$ WD with an unseen $M \geq 1.11\,M_{\odot}$ WD companion in a 1.5-h orbit. With a mass ratio of ≈0.1, J1741 will have stable mass transfer through an accretion disc and turn into an interacting AM Canum Venaticorum (AM CVn) system in the next ≈160 Myr. With a mass ratio of 0.2, J0751 is likely to follow a similar evolutionary path. These are the first known AM CVn progenitor binary systems and they provide important constraints on the initial conditions for AM CVn. Theoretical studies suggest that both J0751 and J1741 may create thermonuclear supernovae in $\sim 10^8$ yr, either .Ia or Ia. Such explosions can account for ∼1 per cent of the Type Ia supernova rate.

**Key words:** binaries: close – stars: individual: SDSS J075141.18−014120.9 – stars: individual: SDSS J174140.49+652638.7 – white dwarfs – Galaxy: stellar content.

## 1 INTRODUCTION

AM Canum Venaticorum (AM CVn) are interacting binary systems involving an accreting white dwarf (WD) and a helium-rich donor star, which may be either low-mass WDs, helium stars, or evolved main-sequence stars. There are currently more than 30 AM CVn stars known with orbital periods ranging from 5.4 min (Roelofs et al. 2010) to 65 min (Carter et al. 2013; Levitan et al. 2013). The prototype of the class, AM CVn, was discovered by Smak (1967), but the relative importance of the proposed birth channels is still not well understood. The problem is that all three channels lead to the same donors: very low mass ($<0.1\,M_{\odot}$) degenerate dwarfs (Nelemans et al. 2010). Studying the chemical abundances of 11 AM CVn systems, Nelemans et al. (2010) find evidence for WD donors in three systems, but the donor type is not clear for the remainder of their sample.

The orbital evolution of AM CVn is initially dominated by gravitational wave radiation. However, after the mass transfer starts to dominate the evolution, the orbital period goes through a minimum and then increases (Solheim 2010). For the shortest period AM CVn, the mass transfer rate is high enough that the accreted helium on to the CO WD undergoes unstable, nova-like outbursts. As the orbital period increases the mass transfer rate decreases, and the required mass for unstable burning goes up, leading to a final flash with a helium layer mass of ∼0.02–0.1 $M_{\odot}$. This occurs within $<10^8$ yr of reaching contact. Bildsten et al. (2007) find that the final flash for a >0.7–0.9 $M_{\odot}$ CO WD is likely to be dynamical, leading to the ejection of radioactive $^{48}$Cr, $^{52}$Fe, and $^{56}$Ni. This might lead to a faint and rapid thermonuclear supernova (SN) .Ia. Such a transient event might have already been observed (Kasliwal et al. 2010, though see Drout et al. 2013).

Given the difficulties in disentangling the component masses in AM CVn, the identification of their progenitor systems would be

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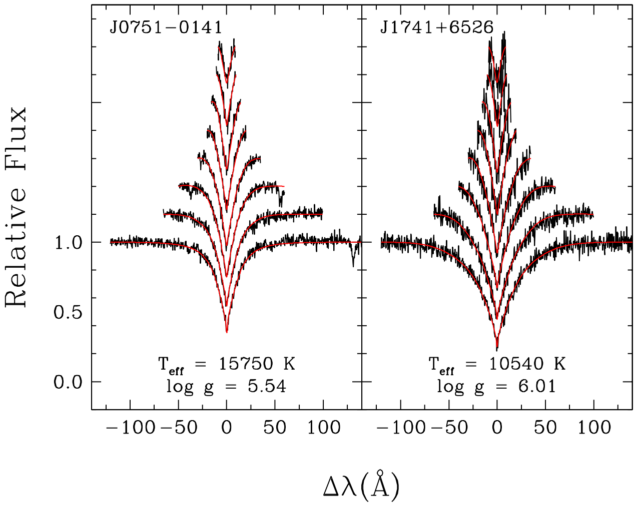

**Figure 1.** Model fits (red lines) to the Balmer line profiles of J0751 and J1741. H$\gamma$ (bottom) through H12 (top) are shown.

extremely useful for constraining the initial conditions for AM CVn and possible SNe. Ia explosions. Here, we present the identification of two such progenitor systems, SDSS J075141.18−014120.9 (J0751) and SDSS J174140.49+652638.7 (J1741). Both were discovered in the ELM (Extremely Low Mass) Survey (Kilic et al. 2012; Brown et al. 2013) as short period binaries with massive companions. We obtained follow-up optical and X-ray observations to constrain the nature of the ELM WDs and their unseen companions. Our observations are discussed in Section 2, and the binary parameters are discussed in Section 3. Evolutionary scenarios for the future of these systems are presented in Section 4.

## 2 OBSERVATIONS

### 2.1 Optical spectroscopy

Optical spectroscopy of the ELM WDs in J0751 and J1741 were previously presented by Brown et al. (2012, 2013). J1741 was originally found to be one of the lowest surface gravity WDs known, with a spectroscopically determined $\log g < 5.2$. However, this low surface gravity is incompatible with the relatively small inferred radius of the ELM WD determined from the ellipsoidal variations observed in its optical light curve (Hermes et al. 2012). We used an extended model atmosphere grid based on the Tremblay & Bergeron (2009) models to re-evaluate the spectroscopic temperature and surface gravity for both J0751 and J1741. Fig. 1 shows our model fits to the Balmer line profiles of both stars.

The best-fitting model for J0751 has $T_{\rm eff} = 15\,750 \pm 240$ K and $\log g = 5.54 \pm 0.05$. The recent evolutionary calculations by Althaus, Miller Bertolami & Córsico (2013) demonstrate that J0751 is a 280 ± 140 Myr old, 0.194(6) $\mathrm{M}_{\odot}$ and $M_g = 6.1$ mag WD, at a distance of 1.7 ± 0.1 kpc. The best-fitting model for J1741 has $T_{\rm eff} = 10\,540 \pm 170$ K and $\log g = 6.01 \pm 0.06$. The evolutionary models indicate that J1741 is a 1.6 ± 0.1 Gyr old, 0.168(5) $\mathrm{M}_{\odot}$ and $M_g = 8.3$ mag WD, at a distance of 970 ± 45 pc. The systematic uncertainties in these mass estimates are likely around 10 per cent, or 0.02 $\mathrm{M}_{\odot}$.

### 2.2 Optical photometry

We obtained high-speed photometry of J0751 from two sites between 2012 February and 2013 April. We obtained 45.3 h (5–30 s exposures) and 17.9 h (30–45 s exposures) of data using the Argos (Nather & Mukadam 2004) and the Puoko-nui (Chote & Sullivan 2013) instruments on the McDonald Observatory 2.1 m and the Mt John Observatory 1.0 m telescopes, respectively. All observations were obtained through a BG40 filter. Hermes et al. (2012) obtained 9.5 h of photometry for J1741 using Argos on the McDonald 2.1 m telescope in 2011 May and September. We obtained an additional 3.5 h of high-speed photometry with 15–30 s exposures and the same setup in 2012 June and July. Our data reduction procedures are described in Hermes et al. (2012).

### 2.3 X-ray observations

If the companions to J0751 and J1741 are neutron stars (NS), they would have been spun up to millisecond periods during the primary's red giant phase. Such millisecond pulsars (MSPs) would be detected in X-rays even if they were radio quiet or if their pulsar beams were missing our line of sight, due to gravitational bending of the X-rays originating from the surface (Beloborodov 2002). We are motivated by the X-ray detection of all known MSPs in the globular cluster 47 Tuc (Heinke et al. 2005), allowing predictions of the X-ray emission of other MSPs. We observed both J0751 and J1741 with *Chandra*'s ACIS-S detector in a Very Faint mode, for 4.0 (on 2012 December 22) and 6.0 (on 2013 January 18) ks, respectively. We reprocessed the raw *Chandra* data using CIAO 4.5. Inspection of the 0.3–7 keV images showed no counts within 1 arcsec of the position of either WD (well beyond the 0.6 arcsec 90 per cent confidence region for *Chandra* astrometry), and only 1 or 0 counts within 5 arcsec of J0751 or J1741, respectively.

We also obtained a 4.8 ks *XMM* observation of J1741 on 2012 October 25. We analysed the standard pipeline products using SAS v13.0.0. Although the background was variable, we did not reject any times based on high background, leaving us with 4.8, 4.7 and 3.2 ks of good time for the MOS1, MOS2 and pn detectors, respectively. We filtered the data using standard filters for soft data, and selecting the 0.2–1.5 keV energy range for the most effective selection of soft sources. No source is visible within 1 arcmin of J1741 in any camera. We measure the counts within an 8 arcsec region around J1741's position, which would contain 50 per cent of the 1.5 keV photons from a source at that position. Including background subtraction, we find $2\sigma$ upper limits of 15, 5 and 5 counts from J1741 in the pn, MOS1 and MOS2 error circles.

To infer upper limits on the X-ray flux of our targets, we first use the COLDEN tool to interpolate the Dickey & Lockman (1990) H I survey, and estimate $N_{\rm H}$ values of $5.9 \times 10^{20}$ cm$^{-2}$ and $3.7 \times 10^{20}$ cm$^{-2}$ towards J0751 and J1741, respectively. Since both targets are well above the Galaxy's H I disc (0.15 kpc scaleheight; e.g. Kalberla & Kerp 2009), we assume the full Galactic extinction. We use the PIMMS tool to compute the unabsorbed 0.3–8 keV flux for a 134 eV blackbody (appropriate for the faintest 47 Tuc MSP). We calculate 95 per cent confidence upper limits to the 0.3–8 keV X-ray fluxes, and thus to the 0.3–8 keV luminosities. We calculate upper limits on the true count rate, using the observed count rate and Poisson statistics (Gehrels 1986); so for the *Chandra* observations, we used upper limits of 3 counts, corresponding to 95 per cent confidence when 0 counts are observed. This gives $F_X$ upper limits of $3.7 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for J1741 and $6.5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for J0751. We then use the $2\sigma$ upper limits on the distances (i.e. 1060 pc for J1741 and 1968 pc for J0751, see Section 2.1) to find upper limits of $L_X < 3.0 \times 10^{30}$ and $5 \times 10^{29}$ erg s$^{-1}$ for J0751 and J1741, respectively. We confirm our result for J1741 using the *XMM* observation, which gives an upper limit of $L_X < 1.7 \times 10^{30}$ erg s$^{-1}$ from each of the pn and (combined) MOS cameras.

For J1741, our best 95 per cent confidence upper $L_X$ limit of $5 \times 10^{29}$ erg s$^{-1}$ is well below the luminosity of any MSP in 47 Tuc, using the blackbody fluxes reported in Bogdanov et al. (2006) and a 4.5 kpc distance (Harris 1996, 2010 revision). For J0751, however, our new estimate of a higher distance means that our requested observing time was insufficient to completely exclude MSP fluxes, giving an $L_X$ upper limit above 6 (of 19) of the 47 Tuc MSPs. We can also select a 1$\sigma$ upper limit (using an upper limit of 1.8 counts, and increasing the best-fitting distance by only 1$\sigma$), finding $L_X$(0.3–8 keV) $<1.67 \times 10^{30}$ erg s$^{-1}$. This is fainter than all but 1 (of 19) MSPs in 47 Tuc. We conclude that our X-ray observations decisively reject an NS companion for J1741, and present strong (but not conclusive) evidence against an NS companion for J0751. A Green Bank Telescope radio search has also failed to detect MSP companions in both systems (Andrews, private communication).

## 3 BINARY PARAMETERS

### 3.1 J0751

J0751 shows $K = 432.6 \pm 2.3$ km s$^{-1}$ velocity variations with an orbital period of 0.08001 ± 0.00279 d (Brown et al. 2013). Fig. 2 shows J0751's optical light curve. A Fourier transform of our photometric data set shows a well-resolved peak at 57.609 07(3) min due to 3.20 ± 0.11 per cent ellipsoidal variations. We use this signal to improve our estimate of the orbital period to 0.080 012 60(4) d. The revised mass function is $f = 0.671 \pm 0.011$ M$_\odot$, which yields a minimum companion mass of 0.97 ± 0.01 M$_\odot$. The non-detection of an NS companion constrains the inclination to $i \geq 58.^{\circ}6$. We detect a slight asymmetry in the maxima of the folded light curve due to a 0.24 ± 0.11 per cent Doppler beaming signal (Zucker, Mazeh & Alexander 2007). We also see substantially depressed minima at Phase 1 that do not appear fully represented by a model of ellipsoidal variations and Doppler beaming. These features are evidence of eclipses of the low-mass primary, which makes J0751 the fifth eclipsing double WD known and provides further constraints on the system parameters. We use JKTEBOP (Southworth et al. 2005) and the limb darkening coefficients of Gianninas et al. (2013) to model this system, although our results are highly uncertain due to the relatively large scatter of the data at Phase 1. The best-fitting model has $i = 85.4^{+4.2}_{-9.4}$ deg, $R_1 = 0.155 \pm 0.020$ R$_\odot$, $R_2 = 0.0092 \pm 0.0026$ R$_\odot$ and $M_2 = 0.97^{+0.06}_{-0.01}$ M$_\odot$. The errors in these parameters are calculated from $10^5$ Monte Carlo simulations and represent 95.5 per cent (2$\sigma$) errors. Based on the $\log g$ measurement and inferred mass, the radius should be $R_1 = 0.124 \pm 0.014$ R$_\odot$, which agrees reasonably with our light-curve analysis. Additional observations of the eclipses will be useful for more precise constraints on this system.

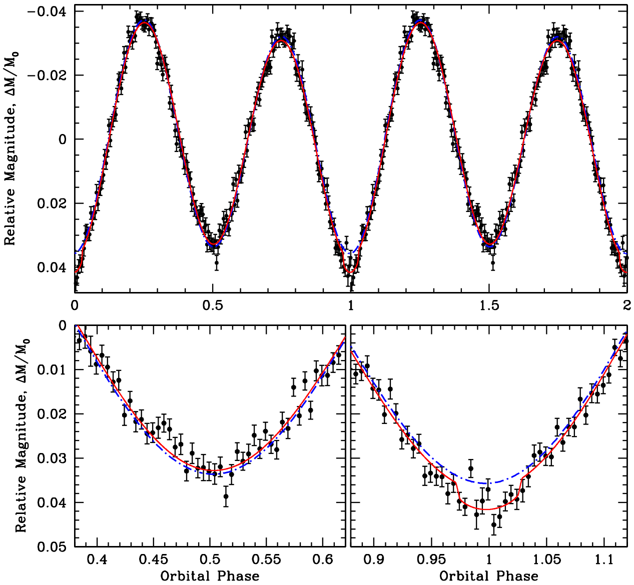

**Figure 2.** High-speed photometry of J0751 folded at the orbital period, binned into 200 phase bins, and repeated for clarity. The dotted blue line shows a model fit including ellipsoidal variations and Doppler beaming. The solid red line shows the best-fitting model including primary eclipses.

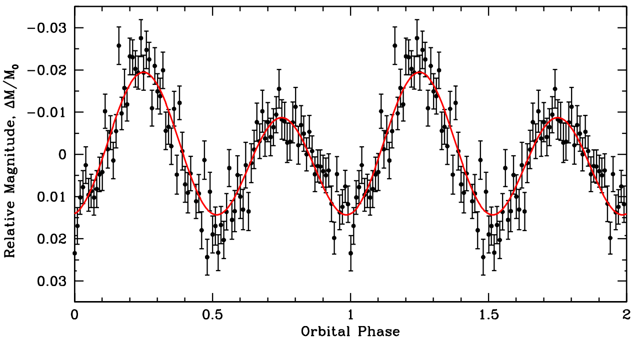

**Figure 3.** High-speed photometry of J1741, folded at the orbital period and repeated for clarity. The red line shows the best-fitting model including ellipsoidal variations and Doppler beaming.

### 3.2 J1741

J1741 shows $K = 508 \pm 4$ km s$^{-1}$ velocity variations with an orbital period of $P = 0.061\,11 \pm 0.000\,01$ (Brown et al. 2012). The mass function is $f = 0.830 \pm 0.018$ M$_\odot$, and the minimum companion mass is 1.10 ± 0.01 M$_\odot$. The lack of an NS companion requires $i \geq 64.^{\circ}9$. Fig. 3 shows the optical light curve of J1741, which exhibits significant evidence for both Doppler beaming (0.50 ± 0.08 per cent) and ellipsoidal variations (1.30 ± 0.08 per cent). Hermes et al. (2012) noted that they might have also detected a reflection effect at the 2$\sigma$ level, but our additional data demonstrate that there is no significant reflection effect in this system.

There are no signs of eclipses in our light curve at the 4$\sigma$ level of 0.32 per cent. This constrains the inclination to $i \leq 84.^{\circ}4$ and $M_2 \geq 1.11$ M$_\odot$. Based on the uncertainties in the spectroscopic surface gravity and derived mass, we expect the primary to have a radius of $R_1 = 0.067 \pm 0.005$ R$_\odot$. The amplitude of the ellipsoidal variations constrain $R_1$ to 0.069–0.079 R$_\odot$ over the allowed inclinations of $i = 64.^{\circ}9$–$84.^{\circ}4$. Both values are in good agreement.

## 4 THE FUTURE

### 4.1 AM CVn

Our optical and X-ray observations demonstrate that J0751 is a 0.19 ± 0.02 M$_\odot$ WD with a $0.97^{+0.06}_{-0.01}$ M$_\odot$ WD companion in a $P = 115$ min binary. Similarly, J1741 is a 0.17 ± 0.02 M$_\odot$ WD with an unseen $M \geq 1.11$ M$_\odot$ WD companion in a $P = 88$ min binary. Assuming energy and angular momentum loss due to gravitational wave radiation, the ELM WDs in J0751 and J1741 will reach their

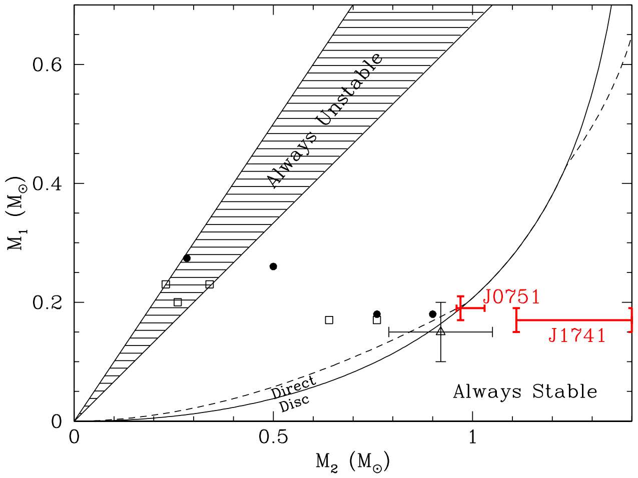

**Figure 4.** Mass transfer stability for double WDs (Marsh et al. 2004). Disc accretion occurs in the region below the solid line. J1741 (J0751) is clearly (likely) in this parameter range; it will evolve into a stable mass transfer AM CVn. Eclipsing double WD systems (filled circles), other ELM WD merger systems with X-day data (open squares), and double-lined binary WD system J1257+5428 (open triangle) are also shown.

Roche lobe radii and start mass transfer in about 270 and 160 Myr, respectively.

The stability of the mass transfer between double WDs depends on the mass ratio and the degree of the spin–orbit coupling. Fig. 4 shows the dynamical stability limit of Marsh, Nelemans & Steeghs (2004) for different primary and secondary mass WDs. For $q = M_2/M_1 > 2/3$, the mass transfer is unstable, leading to merger. For small $q$ ($\leq$0.2), stable mass transfer occurs through direct impact or disc accretion. For the intermediate cases, the stability depends on the synchronization time-scale of the system. J1741 is clearly in the parameter range for stable mass transfer through disc accretion. It will reach contact in $\sim 10^8$ yr and is destined to become a stable mass transfer AM CVn system. This is the first identified progenitor of AM CVn. With a mass ratio of $q = 0.2$, J0751 may also turn into an AM CVn. However, the stability of mass transfer and the future of J0751 are uncertain due to the unknown synchronization time-scale.

Fig. 4 includes nine other double WD systems with mass constraints from X-ray observations or eclipses. There are five ELM WD merger systems with X-ray data (Kilic et al. 2011, 2012), and none show evidence of an NS companion. The lower limit on the companion mass for each of these five objects are shown as open squares. Given the unknown inclination and thus unknown companion mass, the future of these objects is unclear. Out of the four eclipsing double WD systems previously known (Steinfadt et al. 2010; Brown et al. 2011b; Parsons et al. 2011; Vennes et al. 2011), two have $q > 0.5$; these will likely merge. The future of the remaining two systems depends on the degree of the spin–orbit coupling. Fig. 4 includes another potential AM CVn progenitor, the double-lined spectroscopic binary SDSS J1257+5428 (Kulkarni & van Kerkwijk 2010; Marsh et al. 2011). Given the difficulties in disentangling the spectra of the individual WDs in this system, the mass estimates are uncertain; $M_1 = 0.15 \pm 0.05\,\mathrm{M}_\odot$, $M_2 = 0.92 \pm 0.13\,\mathrm{M}_\odot$. Hence, the future of this binary is also unsettled. Fig. 4 shows that J1741 ($q = 0.12$–$0.15$) is unique as the first confirmed progenitor of stable-mass transfer AM CVn.

Roelofs, Nelemans & Groot (2007) used six AM CVn found in the SDSS spectroscopic data base to estimate an AM CVn space density of $1.5 \times 10^{-6}\,\mathrm{pc}^{-3}$. After an extended search for AM CVn in the SDSS, Carter et al. (2013) revised the space density estimate to $5 \pm 3 \times 10^{-7}\,\mathrm{pc}^{-3}$, a factor of 3 smaller (see Nissanke et al. 2012). Using the former estimate, Brown et al. (2011a) demonstrated that ELM WD binaries can explain 2–4 per cent of the AM CVn birthrate. Given the lower space density of AM CVn and the larger number of ELM WDs binaries now known, ELM WDs with massive companions can explain a significant fraction of AM CVn.

### 4.2 SNe .Ia or Ia

Recent studies by Shen & Bildsten (2009) and Shen et al. (2010) confirm that AM CVn with $\geq 0.8\,\mathrm{M}_\odot$ accretors will achieve dynamical burning with envelope masses of $<0.1\,\mathrm{M}_\odot$. Here, we have uncovered at least one (and perhaps two) binary WD that should explode as SN .Ia in the next several hundred Myr. Both J0751 and J1741 contain ELM WDs with $M > 0.9\,\mathrm{M}_\odot$ companions. J1741 will start stable mass transfer in $\approx$160 Myr and will likely have a faint, thermonuclear explosion within $10^8$ yr after that. Depending on the degree of spin–orbit coupling and the stability of mass transfer, J0751 may follow a similar evolutionary path.

The envelope masses of $0.1\,\mathrm{M}_\odot$ are too small to be relevant for the double-detonation models of Nomoto (1982), Livne (1990) and Woosley & Weaver (1994). However, Fink et al. (2010) find it inevitable that core detonation occurs after a helium shell detonation on 0.94–1.39 $\mathrm{M}_\odot$ CO WDs with shell masses of 0.0035–0.126 $\mathrm{M}_\odot$. Shen & Bildsten (2013) also support the double-detonation scenario for AM CVn; they find that helium shell detonations create converging shocks in the core. These shocks are strong enough to ignite carbon and create SNe Ia events (also see Moll & Woosley 2013). This scenario essentially turns the SNe .Ia candidates into Type Ia candidates, and could explain a fraction of thermonuclear SNe (Ruiter et al. 2011). Pakmor et al. (2013) argue that the helium-ignited mergers of CO+CO and CO+He binary WDs can explain the observed diversity of SNe Ia. In their model, a thin helium shell is ignited even in the CO+CO WD merger, explaining normal and brighter Ia, whereas CO+He binary WDs may lead to fainter SNe due to lower ejecta mass.

A remaining problem with the double-detonation model for AM CVn is that the explosion models can match the light curves of SNe Ia but not their colours and spectra (Kromer et al. 2010). This is mostly due to the effects of helium burning on the resulting spectra. However, good agreement between sub-Chandrasekhar-mass explosions and SNe Ia may still be feasible depending on the initial composition of the helium shell. Townsley, Moore & Bildsten (2012) demonstrate that if post-shock radial expansion of the helium layer is taken into account, the predicted colours and spectral features would be consistent with normal SNe Ia, except when the effects of the extremely small helium shell is seen at earliest times.

An alternative endpoint for AM CVn involves core detonation, if the CO WD is already close to the Chandrasekhar-mass limit. This channel likely contributes $\leq$1 per cent to the SNe Ia rate (Solheim & Yungelson 2005). The combined mass of the primary and secondary WDs in J0751 is $\approx 1.16\,\mathrm{M}_\odot$. On the other hand, J1741's companion may be massive enough to reach the Chandrasekhar-mass limit through accretion from the ELM WD. Unfortunately, the core composition of the companions in these two systems is not known. If they have ONe cores, then the double-detonation scenario is highly unlikely as it is extremely difficult to ignite O-burning (Shen & Bildsten 2013). In addition, accretion from the companion may instead lead to an accretion-induced collapse to an NS (Nomoto & Kondo 1991).

## 5 CONCLUSIONS

Direct discovery of the detached progenitors of AM CVn stars as well as SNe .Ia and Ia has so far been elusive. Recent theoretical studies suggest that sub-Chandrasekhar mass WDs in accreting systems, including AM CVn, may create thermonuclear SNe. Ignition of a thin helium layer on an accreting CO WD may lead to .Ia explosions, and potentially SNe Ia. Regardless of the theoretical problems in our understanding of the final outcome of helium-shell detonations, it is clear that AM CVn with $M \geq 0.8\,\mathrm{M}_{\odot}$ accretors are extremely interesting. However, the component masses in AM CVn are rarely known and highly uncertain.

In this paper, we present the first confirmed progenitor(s) of AM CVn stars. J0751 and J1741 are short period binary systems containing 0.17–0.19 $\mathrm{M}_{\odot}$ ELM WDs and $M > 0.9\,\mathrm{M}_{\odot}$ WD companions. Due to its extreme mass ratio, J1741 will start stable mass transfer and likely explode as SN .Ia in the next several hundred Myr. With $q = 0.2$, J0751 is also a likely AM CVn and SN .Ia progenitor. Depending on the companion masses and the core composition, these systems may also detonate as SNe Ia. One has to wait only $\sim 10^8$ yr to know the answer.

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