Spectroscopic and Photometric Periods of Six Ultracompact Accreting Binaries

Matthew J. Green\textsuperscript{1}\textsuperscript{*}, Thomas R. Marsh\textsuperscript{1}\textsuperscript{†}, Philip J. Carter\textsuperscript{2}, Danny Steeghs\textsuperscript{1}, Elmé Breedt\textsuperscript{3}, V. S. Dhillon\textsuperscript{4,5}, S. P. Littlefair\textsuperscript{4}, Steven G. Parsons\textsuperscript{4}, Paul Kerry\textsuperscript{4}, Nicola P. Gentile Fusillo\textsuperscript{6}, R. P. Ashley\textsuperscript{1}, Madelon C. P. Bours\textsuperscript{1}, Tim Cunningham\textsuperscript{1}, Martin J. Dyer\textsuperscript{4}, Boris T. Gänscike\textsuperscript{1}, Paula Izquierdo\textsuperscript{5,7}, Anna F. Pala\textsuperscript{6}, Chuangwit Pattama\textsuperscript{8}, Sabrina Outmani\textsuperscript{1}, David I. Sahman\textsuperscript{4}, Boonchoo Sukaum\textsuperscript{8}, and James Wild\textsuperscript{4}.

\textsuperscript{1}Astronomy and Astrophysics Group, Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom
\textsuperscript{2}Department of Earth and Planetary Sciences, University of California Davis, One Shields Avenue, Davis, CA 95616
\textsuperscript{3}Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, United Kingdom
\textsuperscript{4}Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, United Kingdom
\textsuperscript{5}Instituto de Astrofísica de Canarias, 38205 La Laguna, Tenerife, Spain
\textsuperscript{6}European Southern Observatory, Karl Schwarzschild Straße 2, Garching, 85748, Germany
\textsuperscript{7}Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain
\textsuperscript{8}National Astronomical Research Institute of Thailand (Public Organization), 260 Moo 4, Donkaew, Mae Rim, Chiang Mai, 50180, Thailand

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Ultracompact accreting binary systems each consist of a stellar remnant accreting helium-enriched material from a compact donor star. Such binaries include two related sub-classes, AM CVn-type binaries and helium cataclysmic variables, in both of which the central star is a white dwarf. We present a spectroscopic and photometric study of six accreting binaries with orbital periods in the range of 40–70 min, including phase-resolved VLT spectroscopy and high-speed ULTRACAM photometry. Four of these are AM CVn systems and two are helium cataclysmic variables. For four of these binaries we are able to identify orbital periods (of which three are spectroscopic). SDSS J1505+0659 has an orbital period of 67.8 min, significantly longer than previously believed, and longer than any other known AM CVn binary. We identify a WISE infrared excess in SDSS J1505+0659 that we believe to be the first direct detection of an AM CVn donor star in a non-direct impacting binary. The mass ratio of SDSS J1505+0659 is consistent with a white dwarf donor. CRTS J1028–0819 has an orbital period of 52.1 min, the shortest period of any helium cataclysmic variable. MOA 2010-BLG-087 is co-aligned with a K-class star that dominates its spectrum. ASASSN-14ei and ASASSN-14mv both show a remarkable number of echo outbursts following superoutbursts (13 and 10 echo outbursts respectively). ASASSN-14ei shows an increased outburst rate over the years following its superoutburst, perhaps resulting from an increased accretion rate.

Key words: stars: dwarf novae – novae, cataclysmic variables – binaries: close – white dwarfs

1 INTRODUCTION

Cataclysmic variables (CVs) are compact, interacting binaries. Each CV consists of a white dwarf accreting material

\textsuperscript{*} E-mail: mjgreenastro@gmail.com
\textsuperscript{†} E-mail: t.r.marsh@warwick.ac.uk

© 2020 The Authors
79.6 ± 0.2 min (Knigge et al. 2011; McAllister et al. 2019). Accreting binaries which have orbital periods shorter than this limit must therefore have donors which were not typical main-sequence stars at the point of first contact. The most common explanation for the donor to be evolved, with a helium-rich nature and consequently greater density that allows the binary to exist at shorter orbital periods. CVs with evolved donors and periods shorter than the canonical period minimum can be divided into two sub-classes: helium-rich CVs (He CVs), which accrete helium-enriched material containing some amount of hydrogen, and AM Canum Venaticorum (AM CVn) type binaries, which accrete helium-dominated material with no detectable hydrogen. AM CVn binaries include the shortest-period systems known (Motch et al. 1996; Israel et al. 1999; Steeghs et al. 2006; Roelofs et al. 2010), and are expected to be among the strongest Galactic sources of gravitational wave radiation in the LISA frequency range (Kremer et al. 2017; Breivik et al. 2018; Kupfer et al. 2018). Although He CVs and AM CVn binaries are similar in appearance, the extent to which they are evolutionarily related is not yet well understood.

The formation path of a He CV is as follows. In a volume-limited sample, 5±3 per cent of CVs appear to have evolved donors (Pala et al. 2020). The majority of these donor stars still have hydrogen-dominated atmospheres and orbital periods longer than the canonical period minimum. Over time, mass transfer will strip away the atmosphere of the donor star, revealing the helium-enriched core. In this manner the accreted material becomes helium-rich. At the same time, the increasing density of the donor star will require that the binary evolves to a shorter orbital period.

The evolution of AM CVn binaries is uncertain, with three proposed channels (see Solheim 2010 for an overview, and Green et al. 2018b and Ramsay et al. 2018 for recent results). In two of these channels, the binary goes through two phases of common envelope evolution (Ivanova et al. 2013), leaving either a double white dwarf binary (Paczyński 1967; Deloye et al. 2007) or a binary consisting of a white dwarf and a helium-burning star whose atmosphere has been stripped during the common envelope evolution (Savonije et al. 1986; Iben & Tutukov 1987; Yungelson 2008).

In the third suggested channel of AM CVn evolution, the AM CVn binary descends directly from a He CV in which the core of the donor star is sufficiently helium-enriched (Podsiadlowski et al. 2003; Goliach & Nelson 2015). As a source of AM CVn binaries, this channel has several uncertainties. Firstly, the region of initial parameter space for which a binary may be able to remove all detectable hydrogen from the accreted material is rather small, and many He CVs will never successfully remove enough hydrogen to become AM CVn binaries (Goliach & Nelson 2015). As such we might expect the number of known, sub-period minimum He CVs to provide an approximate upper limit on the number of AM CVn binaries formed by this channel. Secondly, the majority of AM CVn binaries that do form by this channel are not expected to reach periods shorter than ≳ 45 min (Podsiadlowski et al. 2003; Goliach & Nelson 2015). As a result, population synthesis models generally disfavor this model for short period AM CVn binaries compared to the two previously discussed, predicting a contribution of order a few per cent to the population of AM CVn binaries with periods ≲ 30 min (Nelemans et al. 2004; Goliach & Nelson 2015). For AM CVn binaries with orbital periods > 45 min, however, this channel remains a viable option. Indeed, the most precise to date mass and radius measurements of an AM CVn donor star (from the first fully-eclipsing AM CVn binary, Gaia14aae, which has an orbital period of 50 min) agree best with predictions based on the He CV channel (Green et al. 2018a, 2019).

Further attempts to study the prior evolution of these binaries are limited by the small numbers of such systems which are amenable to characterisation. Key properties to constrain the prior evolution of a binary are its orbital period ($P_{\text{orb}}$) and the ratio of masses of its two stars ($q = M_2/M_1$, where $M_1$ is the mass of the accretor and $M_2$ is the mass of the donor). At present, 56 AM CVn binaries (Ramsay et al. 2018) and 13 sub-period minimum He CVs (see Table 1) are known. Another two He CVs are believed to be below the period minimum due to the low hydrogen content of their accreted material. However, many systems of both classes are too faint for detailed follow-up. Only 33 AM CVn binaries have published, directly measured orbital periods (Green et al. 2018b, and references therein). Note that this number does not include those systems for which an indirect estimate of the orbital period has been made, based either on its superhump period (see the discussion in the following section) or on its outburst properties (Levitan et al. 2015). Only 17 AM CVn binaries (Green et al. 2018b) and six sub-period minimum He CVs (Table 1) have published mass ratio measurements.

In this paper, we present a spectroscopic and photometric study of six short-period accreting binaries, including four AM CVn binaries and two sub-period minimum He CVs (Table 2). Our goal is to use these data to measure the orbital periods and, where possible, mass ratios of these systems, in the hope of exploring their prior evolution.

### 1.1 Photometric Behaviour

We start with a brief overview of the photometric behaviour of CVs and AM CVn binaries, as these binaries exhibit a range of phenomena on various timescales.

Both CVs and AM CVn binaries undergo brightening events known as dwarf nova outbursts. These outbursts are caused by an instability in the temperature and density of the accretion disc, causing the material to temporarily ionise, which in turn causes the system to brighten by ~2-9 mag. This brightening can last of order days to weeks. The outbursts of hydrogen- and helium-dominated discs are broadly similar, though different in some specifics (Lasota 2001; Kotko et al. 2012; Cannizzo & Nelemans 2015). In short-period CVs and AM CVn binaries, the outbursts that are seen generally belong to the subtype of dwarf nova outbursts known as ‘superoutbursts’ (Kotko et al. 2012). Superoutbursts generally last for weeks, and are brighter on average than a typical outburst. Following a superoutburst, some CVs and AM CVn binaries show a series of ‘echo outbursts’, which resemble ordinary dwarf nova outbursts. These are thought to be the result of reflections within the disc of the transition waves that mediate the change from ionised to neutral disc states (Patterson et al. 1998; Meyer & Meyer-Hofmeister 2015). Among AM CVn binaries, there is a steep dependence between the orbital period of the binary and the mass trans-
Six Ultracompact Accreting Binaries

Table 1. Properties of known CVs (not including AM CVn binaries) with orbital periods shorter than 79.6 min. The majority are He CVs, but note that the donor of SDSS J1507+5230 does not appear to be evolved; instead, its orbital period can be explained by the low metallicity and hence increased density of its halo-population donor star. CRTS J0808+3550 and CRTS J1647+4338 do not have measured orbital periods, but are believed to be below the orbital period minimum due to the low hydrogen content of their accreted material. In the case of V485 Cen, \( q \) is derived from spectroscopic studies of dynamics; for all other systems \( q \) is derived from the superhump period. In these cases we have recalculated \( q \) from the Stage B superhump excess using Equation 2.

| Name               | Period (min) | \( q \) | Ref |
|--------------------|--------------|--------|-----|
| CRTS J1028-0819    | 52.1         | 0.25 ± 0.06 | 1.2 |
| SBSS 1108+574      | 55.5         | 0.085 ± 0.015 | 3.4 |
| BOK 45596          | 56.4         | – 0.200 ± 0.007 | 5 |
| V485 Cen           | 59.0         | 0.38 ± 0.13 | 6.7 |
| CRTS J2333-1557    | 62.0         | – | 8 |
| El Psc             | 64.2         | 0.185 ± 0.007 | 9 |
| CRTS J1740+4147    | 64.8         | 0.055 ± 0.006 | 10.1 |
| CRTS J1122-1110    | 65.2         | 0.020 ± 0.007 | 12 |
| V418 Ser           | 65.9         | – | 13 |
| SDSS J1507+5230    | 67           | – | 14.15 |
| ASASSN-16fy        | 70.9         | – | 16 |
| ASASSN-17gf        | 75.6         | – | 17 |
| ASASSN-17ou        | 79.5         | – | 18 |
| CRTS J0808+3550    | –            | – | 19 |
| CRTS J1647+4338    | –            | – | 19 |

Outbursts are rarely seen for systems with periods longer than 85 min. The tightest of these correlations, relating the recurrence time between outbursts to the orbital period, is given by McAllister et al. (2019). This expression includes uncertainties in the relationship itself, following the form of Knigge (2006) but using a larger sample of systems. For stage C superhumps and a sample of 24 systems, McAllister et al. (2019) gives

\[
q(\epsilon) = (0.118 ± 0.003) + (4.45 ± 0.28) \times (\epsilon - 0.025),
\]

where \( \epsilon = (P_{\text{sh}} - P_{\text{orb}})/P_{\text{orb}} \) and \( P_{\text{sh}} \) and \( P_{\text{orb}} \) are the superhump and orbital periods, respectively. For stage C superhumps, this relationship is given by Kato et al. (2009) for a discussion of the differences between superhump stages. It should be noted that these relationships were calibrated based on hydrogen-accreting CVs, and doubts have been raised as to whether such a relationship can be extended to the helium-dominated discs of He CVs or AM CVn binaries (Pearson 2007). For the two AM CVn systems where \( q \) has been measured by both superhump and alternate methods, one is in agreement and the other is not (Roelofs et al. 2006; Copperwheat et al. 2011). Regardless, these relationships are widely used to characterise AM CVn binaries where other methods of measuring \( q \) are not possible (Roelofs et al. 2006; Armstrong et al. 2012; Isogai et al. 2019).

2 OBSERVATIONS

The targets for these observations were selected from known but poorly characterised accreting binaries believed to have orbital periods shorter than the period minimum. While all have been included in previously published lists of short-period binaries (e.g. Breedt 2015; Ramsay et al. 2018), several have no peer-reviewed data available and none have been the subject of detailed follow-up before now. A summary of all observations presented in this work is presented in Table 3.

2.1 VLT Spectroscopy

Five targets were observed using the 8.2 m Very Large Telescope (VLT) at Paranal Observatory, Chile, under observing proposal 095.D-0888. Fainter targets (\( G > 19.5 \)) were observed by FORS2 (the Focal Reducer and low dispersion Spectrograph), a spectrograph with lower dispersion (Appenzeller et al. 1998). Brighter targets were observed by X-shooter, an Echelle spectrograph (Vernet et al. 2011). Each target was observed continuously for two hours. Observations with FORS2 were carried out using the 600B grism and a slit width of 1", giving a resolution \((\lambda/\Delta\lambda)\)
Table 2. Targets observed for this work. Magnitudes are taken from Gaia DR2 (Gaia Collaboration et al. 2018) and are given in the $G$ band, except where otherwise stated. Parallaxes are from Gaia DR2, and distances are calculated using the method described by Kupfer et al. (2018). We have avoided the Gaia magnitude of ASASSN-14ei as it is significantly discrepant from the CRTS $V$ magnitude (at $G=16.4$). See Section 3.3.1 for a discussion of this discrepancy.

| Target           | Coordinates (J2000) | Class     | Quiescent Mag. | Outburst | Parallax (mas) | Distance (pc) |
|------------------|--------------------|-----------|----------------|----------|---------------|---------------|
| SDSS J1505+0659  | 15:05:51.58 +06:59:48.7 | AM CVn    | 19.1           | –        | 6.3(5)        | 160 ± 12      |
| ASASSN-14ei = OX Eri | 02:55:33.39 −47:50:42.0 | AM CVn    | $V=18.0$       | $V=11.9$ | 3.92(5)       | 259 ± 4       |
| ASASSN-14mv = V493 Gem | 07:31:23.26 +20:55:53.4 | AM CVn    | 18.0           | $V=12.8$ | 4.07(12)      | 247 ± 7       |
| MOA 2010-BLG-087  | 18:08:34.85 −26:29:22.8 | AM CVn    | 19.4           | $V=14.7$ | –             | –             |
| CRTS J1028−0819   | 10:28:42.89 −08:19:26.6 | He CV     | 19.4           | $V=14.8$ | 1.4(3)        | 720 ± 200     |
| V418 Ser          | 15:14:53.64 +02:09:34.5 | He CV     | 20.2           | $V=15.8$ | 0.5(6)        | 1200 ± 300    |

Table 3. Observations presented in this paper. For spectroscopic observations we give the wavelength range, while we give the filter for photometric observations.

| Target           | Instrument       | Date       | Wavelength range or filter | Exposure (s) |
|------------------|------------------|------------|--------------------------|--------------|
| Spectroscopy     |                  |            |                          |              |
| SDSS J1505+0659  | VLT + X-shooter  | 2015 Apr 9 | 3200–10100 Å              | 16 × 300     |
| ASASSN-14ei      | VLT + X-shooter  | 2015 Aug 11| 3200–10100 Å              | 22 × 240     |
| ASASSN-14mv      | WHT + ISIS       | 2019 Feb 23| 3850–4600 Å, 5750–9000 Å | 2 × 800 + 5 × 600 |
| MOA 2010-BLG-087 | VLT + FORS2      | 2015 May 14| 3850–6300 Å              | 10 × 240     |
| CRTS J1028−0819  | VLT + X-shooter  | 2015 Apr 9 | 3200–10100 Å              | 18 × 300     |
| V418 Ser         | VLT + FORS2      | 2015 Apr 9 | 3850–6300 Å              | 21 × 240     |
| Photometry       |                  |            |                          |              |
| SDSS J1505+0659  | TNT + ULTRASPEC  | 2014 Jan 27| $g'$                      | 207 × 10     |
| ASASSN-14ei      | NTT + ULTRACAM   | 2019 Mar 28| $u_g g_r r_s$             | 616 × 10     |
| ASASSN-14mv      | NTT + ULTRACAM   | 2018 Jan 18| $u_g g_r r_s$             | 785 × 10     |
| ASASSN-14mA      | NTT + ULTRACAM   | 2018 Nov 09| $u_g g_r r_s$             | 2782 × 5     |
| MOA 2010-BLG-087 | NTT + ULTRACAM   | 2010 Apr 21| $u' g' r'$                | 3030 × 5     |
| V418 Ser         | NTT + ULTRACAM   | 2018 Apr 22| $u' g' r'$                | 2952 × 5     |
|                  |                  | 2016 Dec 14| $g'$                      | 6910 × 1     |
|                  |                  | 2018 Feb 08| $g'$                      | 1923 × 1 + 5047 × 0.5 |
|                  |                  | 2017 Dec 14| $g'$                      | 754 × 10     |
|                  |                  | 2018 Aug 11| $g'$                      | 1346 × 10    |
|                  |                  | 2018 Aug 09| $g'$                      | 1278 × 10    |
|                  |                  | 2010 Apr 21| $u' g' r'$                | 502 × 5.6    |
|                  |                  | 2010 Apr 22| $u' g' r'$                | 1866 × 5.6   |
|                  |                  | 2010 Apr 24| $u' g' r'$                | 1932 × 5.6   |
|                  |                  | 2018 Apr 15| $u_g g_r r_s$             | 597 × 15     |

2.2 WHT Spectroscopy

A further target, ASASSN-14mv, was observed using the Intermediate-dispersion Spectrograph and Imaging System (ISIS) instrument on the 4.2 m William Herschel Telescope (WHT). This target was observed for approximately 75 minutes. ISIS has two optical arms with adjustable central wavelengths. One spectrum was taken with the arms centred on 3900 Å and 8200 Å, to search for calcium and nitrogen, and a further six with the arms centred on 4500 Å and 6600 Å. The R600B and R600R gratings were used, with a GG495 order-sorting filter in the red arm. The slit width was 1.2", giving a resolution of 9200. These spectra were also reduced using PAMELA and MOLLY, using the same procedure as described above for FORS2. Wavelength calibrations were carried out using a CuNe+CuAr arc lamp observed before and after the target, and the flux was calibrated using the standard star LTT 7379.

1 http://deneb.astro.warwick.ac.uk/phsaap/software/
2.3 Survey Photometry

To retrieved data from public-access photometric surveys, including the American Association of Variable Star Observers (AAVSO), the Catalina Real-time Transient Survey (CRTS, Drake et al. 2009), the Palomar Transient Factory (PTF, Rau et al. 2009), the Zwicky Transient Facility (ZTF, Masci et al. 2019), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, Chambers et al. 2016), and the All-Sky Automated Search for SuperNovae (ASAS-SN, Shappee et al. 2014; Kochanek et al. 2017).

Observations of several of our targets have previously been reported through the Variable Star Network (VSNET, Kato et al. 2004). We reference the appropriate VSNET alerts where relevant.

2.4 High-Speed Photometry

Where possible, we collected high-speed photometry of these targets using the cameras ULTRACAM and ULTRASPEC (Dhillon et al. 2007, 2014). ULTRACAM is a triple-beam imaging photometer which uses frame-transfer CCDs to reduce dead-time between exposures to negligible amounts (≈25 ms). For these observations, it was mounted on the 3.5 m New Technology Telescope (NTT) at La Silla Observatory, Chile. For earlier observations the standard Sloan filters were used in the three beams. For more recent observations, custom u′g′r′ filters were used (Dhillon et al. 2018), designed to replicate the wavelength ranges of the standard filters but with a higher throughput (especially in the u′ band). ULTRASPEC is a single-band imaging photometer which also uses frame-transfer CCDs. It is mounted on the 2.5 m Thai National Telescope (TNT) on Doi Inthanon, Thailand. For some observations the g′ band was used, while for other observations we used the custom KG5 filter, a broad filter approximately equal to u′+g′+r′, chosen for its greater throughput (see Hardy et al. 2017, Appendix A).

Data were reduced using the standard ULTRACAM pipeline. Each frame was bias- and dark-subtracted. Pixel sensitivity was corrected for using sky flats observed on the same night. Note that for the u′ band, where magnitudes can differ by ~0.1 mag from the corresponding u′ magnitude. As our photometric data are used only for timing purposes, such approximate calibrations are sufficient.

3 RESULTS

Long-term lightcurves of each system are shown in Figure 1. Average spectra of each object are shown in Figures 2 (objects observed with X-shooter), 3 (objects observed with FORS2), and 4 (the object observed with ISIS). In Figure 5, we show line profiles for the 5876 Å He i line in each system, along with other lines of interest.

3.1 SDSS J1505+0659

SDSS J1505+0659 is a known AM CVn binary discovered by Carter et al. (2014). The system was discovered as part of a spectroscopic survey for AM CVn systems, selecting targets according to their SDSS colours (Carter et al. 2013). The discovery paper included four spectra of the system retrieved from the SDSS database, from which they suggested an orbital period of 50.6 min. The uncertainties on their measured radial velocities were large compared to the amplitude of the variation, due to the low resolution of SDSS spectra. Given this and the small number of data points available at the time, the orbital period was considered preliminary and subject to significant uncertainty.

3.1.1 Spectroscopy

Our combined VLT spectrum of SDSS J1505+0659 is shown in Figure 2. The spectrum consists of a series of narrow helium emission lines imposed on a blue continuum. The profile of these helium emission lines is dominated by a strong central spike emission feature with relatively weak emission wings (Figure 5). Central spike features are seen in many AM CVn binaries, and are emitted from on or near the surface of the accreting white dwarf (Green et al. 2019), though the emission mechanism is uncertain. As was noted by Carter et al. (2014), the strength of the central spike emission seen here is similar to a number of other long-period AM CVn binaries, including SDSS J1208+3550 (orbital period 53.0 min; Kupfer et al. 2013), SDSS J1137+4054 (59.6 min; Carter et al. 2014), and V396 Hya (65.1 min; Ruiz et al. 2001; Kupfer et al. 2016).

Emission features are seen from nitrogen and sodium (we show the latter in Figure 5). The presence of nitrogen emission is reminiscent of GP Com (46.5 min; Nather et al. 1981; Marsh et al. 1990; Kupfer et al. 2016) and V396 Hya (Kupfer et al. 2016). The Na i emission is single-peaked and does not undergo any measurable velocity excursions. As such, we suggest it may share an origin with the He i and He ii central spikes. (Given the weaker strength of the Na i lines, it is unlikely that the small velocity excursions of the central spike, discussed below, would be detected for Na i.)
Figure 1. Long-term lightcurves of the systems presented in this paper, except for MOA 2010-BLG-087. Vertical lines represent the times of our observations, either spectroscopy (solid) or high-speed photometry (dashed). Note that we have not shown the the ASASSN detections of ASASSN-14mv, due to the spurious 1.5 mag offset discussed in Section 3.3.1. Several targets have spurious ASAS-SN detections that coincide with the limiting magnitude of \( \sim 17 \); most notably this includes the bright points of SDSSJ1505+0659.
Figure 2. Average spectra of systems observed with X-Shooter on the 8.2 m VLT. Identified spectral features have been labelled. Grey shaded regions are dominated by telluric absorption, which has not been corrected for. Data have been rebinned by a factor of 5.
It is difficult for neutral sodium and ionised helium to exist at the same temperature range, suggesting that the origin of the central spike emission must be sufficiently extended to include a range of temperatures. In addition, we find a broad absorption feature centred on the Na\textsc{i} 5890-95 Å doublet. Absorption of this breadth is likely to be photospheric in origin. This suggests a cool accreting white dwarf, as it is difficult to reconcile Na\textsc{i} absorption with an atmosphere hotter than \( \sim 10000 \) K.

The detection of sodium combined with a non-detection of calcium is unusual, and is worthy of note as it suggests that atmospheric sodium has been enhanced to levels higher than solar. This may provide insight into the prior nature of the donor star. Sodium can be produced via the Ne-Na cycle in the cores of high-mass main sequence stars (Denisenkov & Ivanov 1987) or in the helium-burning shells of asymptotic giant branch stars (Mowlavi 1999). On the other hand, it should be noted that isolated sodium has been seen in at least one accreting binary with an unevolved, brown dwarf donor (Longstaff et al. 2019).

The central spike feature undergoes periodic, low-amplitude velocity excursions, as shown in the trailed spectrum (Figure 6). These excursions were measured by cross-correlating each of the eight strongest emission lines in each spectrum with a Gaussian function. The radial velocities (RVs) measured in this way follow a sinusoidal modulation with a semi-amplitude of 5.0 \( \pm \) 0.2 km/s, around a systemic velocity (\( \gamma \)) which varies between different emission lines. In other AM CVn binaries, central spike \( \gamma \) values have been explained as a combination of an overall gravitational redshift and wavelength-dependent blueshifts arising from the Stark effect (Morales-Rueda et al. 2003; Kuper et al. 2016; Green et al. 2019). We performed an initial sinusoidal fit to the measured RVs for each line individually, in order to measure \( \gamma \) for each line. The values of \( \gamma \) measured in this way are shown in Table 4. These \( \gamma \) values were then subtracted from the RVs in order to perform a combined sinusoidal fit to all emission lines.

The \( \gamma \)-subtracted data and their best-fit sinusoid are shown in Figure 7, along with a Lomb-Scargle periodogram.
The nominal uncertainties on individual RV measurements, this discrepancy is not surprising. This is the longest orbital period of any known AM CVn binary – the longest periodically published orbital period is that of V396 Hya at 65.1 ± 0.7 min (Ruiz et al. 2001).

When compared to the empirical correlation between orbital period and emission line strength noted by Carter et al. (2013), SDSS J1505+0659 is a clear outlier. For the He I 5876 Å line, we measure an equivalent width (EW) of −37.9 ± 3.2 Å. For a system with an orbital period of 68 min, Carter’s relation would predict an EW of approximately −90 Å. However, there are several other systems with smaller EWs than would be predicted by the correlation, including SDSS J1208+3550 and SDSS J1137+4054. The unexpectedly weak EW of SDSS J1505+0659 may suggest that the disc is unusually weak. There is also likely to be an inclination dependence in the EW which may cause systems to be outliers.

### 3.1.2 Mass Ratio

The mass ratio can be calculated from a combination of other binary properties: the orbital period (P orb), the velocity amplitude (K1), the orbital inclination (i), and the mass of the accretor (M1). The calculation uses Kepler’s law and the necessity that orbital velocity v1 = K1/sin i = 2πr/P orb, where r is the separation of the accreting star from the centre of mass of the system. We have measurements of P orb = 67.8 ± 2.2 min and K1 = 5.0 ± 0.2 km/s from the sinusoidal fit shown in Figure 7. For M1, we assumed 0.8 ± 0.1 M⊙. This value is typical of CV accretors (Pala et al. 2020) and consistent with the two AM CVn accretors which have measured masses (Copperwheat et al. 2011; Green et al. 2018a).

In order to constrain the orbital inclination, we measured the velocity of the peak intensity of the disc-originating emission line wings (ie. the outer two peaks of the triple-peaked line profile). The peak intensity occurred at v_D = 750 ± 250 km/s. This peak emission originates from close to the edge of the accretion disc, at a radius described by (Smak 1981; Warner 1995)

$$v_D^2 = \frac{M_1 G \sin^2(i)}{r_d (0.95 \pm 0.05)^2}. \quad (4)$$

In this equation r_d is the disc radius and G is the gravi-

| Wavelength (Å) | γ (km/s) |
|----------------|----------|
| He II 5876     | −37.9 ± 3.2 |
| He I 5801     | 37.8 ± 2.0 |
| He I 5015     | 21.3 ± 1.6 |
| He I 4713     | 23.8 ± 0.7 |
| He I 4686     | 25.1 ± 1.1 |
| He I 4471     | 39.5 ± 1.0 |

Table 4. Measured systemic radial velocities for the He I and He II lines of SDSS J1505+0659. These systematic velocity shifts were measured using a sinusoidal fit to the measured radial velocities.

Lomb 1976; Scargle 1982; VanderPlas 2018. The sinusoidal fit was produced using a Markov Chain Monte Carlo method (MCMC; Goodman & Weare 2010; Foreman-Mackey et al. 2013). The nominal uncertainties on individual RV measurements were underestimated, as evidenced by a reduced χ² value of significantly more than one. We compensated for this by combining the individual uncertainties in quadrature with an additional uncertainty term. This term was included as a parameter in the MCMC, with a log-uniform prior. In Figure 7 the uncertainties on the RV measurements have been scaled to include this additional uncertainty. The orbital period produced by this process is 67.8 ± 2.2 min.

This newly-measured period is significantly different from the 50.6 min period suggested by Carter et al. (2014). Given the uncertainties on their individual RV measurements, this discrepancy is not surprising. This is the longest orbital period of any known AM CVn binary – the longest previously published orbital period is that of V396 Hya at 65.1 ± 0.7 min (Ruiz et al. 2001).

When compared to the empirical correlation between orbital period and emission line strength noted by Carter et al. (2013), SDSS J1505+0659 is a clear outlier. For the He I 5876 Å line, we measure an equivalent width (EW) of −37.9 ± 3.2 Å. For a system with an orbital period of 68 min, Carter’s relation would predict an EW of approximately −90 Å. However, there are several other systems with smaller EWs than would be predicted by the correlation, including SDSS J1208+3550 and SDSS J1137+4054. The unexpectedly weak EW of SDSS J1505+0659 may suggest that the disc is unusually weak. There is also likely to be an inclination dependence in the EW which may cause systems to be outliers.

3.1.2 Mass Ratio

The mass ratio can be calculated from a combination of other binary properties: the orbital period (P orb), the velocity amplitude (K1), the orbital inclination (i), and the mass of the accretor (M1). The calculation uses Kepler’s law and the necessity that orbital velocity v1 = K1/sin i = 2πr/P orb, where r is the separation of the accreting star from the centre of mass of the system. We have measurements of P orb = 67.8 ± 2.2 min and K1 = 5.0 ± 0.2 km/s from the sinusoidal fit shown in Figure 7. For M1, we assumed 0.8 ± 0.1 M⊙. This value is typical of CV accretors (Pala et al. 2020) and consistent with the two AM CVn accretors which have measured masses (Copperwheat et al. 2011; Green et al. 2018a).

In order to constrain the orbital inclination, we measured the velocity of the peak intensity of the disc-originating emission line wings (ie. the outer two peaks of the triple-peaked line profile). The peak intensity occurred at v_D = 750 ± 250 km/s. This peak emission originates from close to the edge of the accretion disc, at a radius described by (Smak 1981; Warner 1995)

$$v_D^2 = \frac{M_1 G \sin^2(i)}{r_d (0.95 \pm 0.05)^2}. \quad (4)$$

In this equation r_d is the disc radius and G is the gravi-

![Average spectrum of ASASSN-14mv, observed with ISIS on the 4.5 m WHT. Identified spectral features have been labelled. Grey shaded regions are dominated by telluric absorption, which has been corrected for. Data have been rebinned by a factor of 5.](image)
Figure 5. Profiles of He\textsc{i} 5876 Å lines for all five systems (left column), and of other spectral features of interest (right column). In windows centred on the He\textsc{ii} 4686 Å line, the He\textsc{i} 4713 Å line can also be seen.

tational constant. We assume that the disc radius is equal to 0.7 times the radius of the Roche lobe of the accretor, as is often seen in CVs (Warner 1995) and in the eclipsing AM CVn, Gaia14aae (Green et al. 2018a). The Roche lobe radius as a fraction of the orbital separation of the two stars (\(a\)) can be calculated as (Eggleton 1983)

\[
\frac{R_L}{a} = \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1 + q^{-1/3})}.
\]

We combined these constraints using a MCMC routine. The median result was \(q = 0.011^{+0.003}_{-0.001}\), where the uncertainties refer to the 16th and 84th percentiles of the distribution. The corresponding inclination was \(i = 60 \pm 20^\circ\). This mass ratio is similar to that of V396 Hya, the previously longest-period AM CVn binary, which has \(q = 0.014 \pm 0.004\) (Kupfer et al. 2016).

A Doppler map of the system was produced using the 67.8 min orbital period. The He\textsc{i} 4686 Å line was chosen because it has prominent disc emission. The Doppler map is shown in Figure 8. The quality of this map is limited by the small number of spectra, giving the map spoke-like artefacts. Despite this, several features can be distinguished. In addition to the central spike and disc emission, a bright spot can be seen in the top left quadrant. As this is the standard location for the bright-spot in Doppler maps, it provides further support to the RV measurements of the central spike which define the orbital phase. Figure 8 also shows predicted velocity tracks for the infalling matter stream, based on the values from our MCMC fit, which approximately coincide with the bright spot.

3.1.3 Photometry

The long-term lightcurve of SDSS J1505+0659 (Figure 1) shows no activity over the period monitored. There are several ASAS-SN detections that are brighter than the baseline. However, as each is an isolated detection preceded and followed by non-detections, and consistent with the magnitude limit of ASAS-SN, we believe these to be false detections. For an AM CVn of this orbital period, outbursts are not expected due to the low accretion rate.

In high-speed photometry of the system we detect no significant variability. By injecting a sinusoidal signal at the orbital period, and assuming that we would detect any signal that had a Lomb-Scargle peak at four times the mean Lomb-Scargle power, we estimate an upper limit on any orbital signal amplitude at 0.5 per cent of the system brightness.

The spectral energy distribution (SED) of SDSS J1505+0659 is noteworthy. In Figure 9 we show...
Figure 7. Above: Weighted mean RV measurements of SDSS J1505+0659 are shown as black points, while measurements from individual lines are shown as faded, coloured points. The median sinusoidal fit and 2-σ range from a Markov Chain Monte-Carlo sampler is shown in blue, with a best-fit period of 67.8 min. Uncertainties on RV measurements have been increased, as discussed in the text. Below: Lomb-Scargle plot produced from the measured RVs.

Figure 8. Doppler map of SDSS J1505+0659 produced from the 5015 Å He i line, and rotated to the standard orientation based on the RV fit in Figure 7. Emission is dominated by the bright central spike, but an accretion disc and a bright spot can also be seen. Radial spokes are an artefact of poor phase coverage. The superimposed white lines show predicted positions of various components, including: the Roche lobes of the two stars (the lobe of the accretor centred approximately on zero, and the donor star above this, centred on approximately \(v_y = 450\) km/s); the velocities of a ballistic stream of infalling matter; and the Keplerian velocities at each point along the stream. The latter two are shown at positions beginning from the inner Lagrange point and ending at a radius of 0.7 times the Roche lobe radius.

3.2 ASASSN-14ei

ASASSN-14ei (also known as OX Eri) is an AM CVn binary, first detected in superoutburst by ASAS-SN in 2014 July (Prieto et al. 2014a). Follow-up observations reported by Prieto et al. (2014b) include a spectrum showing He i and He ii lines, as well as optical, UV and X-ray imaging with Swift, and a series of rebrightenings following the original outburst. VSNET alert #17575\(^2\) reported a photometric period during outburst of 41.63(3) min, believed to be a superhump period. Based on archival data from the CRTS, they suggest a photometric period of \(\approx 40.0\) min during quiescence, possibly the orbital period.

3.2.1 Long-term Lightcurve

The long-term lightcurve of ASASSN-14ei is shown in Figure 1. There are several unusual features in the long-term lightcurve of ASASSN-14ei. No outburst activity is detected during the CRTS coverage before the 2014 superoutburst. Then, following the original superoutburst in 2014, a series of 12 echo outbursts were seen and were followed by a non-thermal component originating at the accretion disc could also result in this SED.

\(^2\) http://ooruri.kusastro.kyoto-u.ac.jp/mailarchive/vsnet-alert/17575
the AAVSO. Since the end of the echo outbursts, a number of standard outbursts have been seen with a recurrence time of less than 100 days, shorter than is generally seen in AM CVn binaries. In addition, since the superoutburst, the magnitude of the system between outbursts (in both ASAS-SN and AAVSO data) is brighter than the CRTS magnitude before superoutburst by around 1 mag. We will discuss each of these features in turn.

The series of 12 echo outbursts following the 2014 superoutburst were observed intensively by the AAVSO. The lightcurve of these outbursts is shown in Figure 10. Such a large number of echo outbursts is highly unusual, having been seen in only one previous system, WZ Sge (Patterson et al. 2002). It can be seen in the top panel of Figure 10 that the time separation of these echo outbursts increases over time. In the bottom right panel of Figure 10 we show the separation between each measured echo outburst. The separation between outbursts increases approximately linearly with the elapsed time since the original superoutburst.

During these echo outbursts, a roughly sinusoidal variation in brightness is seen. In order to measure the period of this signal, we divided the available AAVSO data by observer and then by night. For each of the resulting sections, a Lomb-Scargle periodogram was produced. From all of the periodograms produced in this way, we selected those in which the signal was visible. The mean period from these periodograms produced in this way, we selected those in match the Roche lobe radius of the donor star, and the black dashed curve shows the sum of the two blackbody spectra. The addition of the second blackbody explains the infrared excess seen in the UKIDSS and WISE data.

3.2.2 High-speed Photometry

We obtained high-speed photometry of ASASSN-14ei with ULTRACAM across four nights, one in 2018 January and three in 2018 November (Figure 12). The system was not in outburst for any of these observations, although a difference in magnitude can be seen between January and November (consistent with the decreasing trend in brightness noted in the previous section).

On January 21, the strongest signal has a period of 44.6 min. Across two consecutive nights, November 9 and November 10, periods can be seen at 86.9 min and 88.7 min respectively. On November 12, this signal is not seen. It may be that the signal from January 21 is a harmonic of the signal seen on November 9 and 10, as the periodogram does show a smaller peak at around this frequency. We do not
know of any physical process that would produce a signal in the 80–90 min range, but note that AM CVn binaries have been known to show quasi-periodic oscillations at a variety of frequencies (Fontaine et al. 2011). None of these signals is consistent with the periods discussed previously in this paper: neither the period we measured from the AAVSO outburst data (42.85 ± 0.14 min), nor the period measured by VSNET during outburst (41.63 ± 0.03 min), nor the suggested period during quiescence from CRTS (≈ 40.0 min).

We also note that a signal with a period of approximately 10.5 min appears to be present in data from all four nights. Such a signal could perhaps be related to the spin period of the central white dwarf, but may also be a quasi-periodic oscillation.

3.2.3 Spectroscopy

The mean X-shooter spectrum of ASASSN-14ei is shown in Figure 2. A series of helium emission lines are seen, including both He I and He II. Several metal lines are also seen, including calcium, nitrogen, and silicon in emission and magnesium and sodium in absorption. The nitrogen lines are notably weaker than in SDSS J1505+0659. The presence of magnesium absorption is interesting. A trailed spectrum shows no notable velocity excursions from the magnesium triplet, suggesting that it originates from the central white dwarf. This may imply a low temperature for the central white dwarf, given the low ionisation energy of magnesium. If the mass transfer rate of the system is indeed elevated as suggested in the previous section, this low temperature would be unexpected.
Figure 11. Separations between the times of each normal outburst and its preceding outburst for ASASSN-14ei are shown as blue points. This figure shows isolated outbursts, not including echo outbursts, which were shown in Figure 10. All outburst detections shown here are from ASAS-SN or AAVSO. Grey vertical dashes at the top of the plot denote the times of ASAS-SN observations; there is no significant decrease in cadence to explain the growing separations of detected outbursts. Red highlighted regions denote significant gaps in coverage due to the star being behind the sun. The data point following each gap has been coloured red to show that it may be unreliable (as preceding outbursts may have been missed during the gap). The dashed black line shows a linear least-squares fit to all blue points, highlighting the trend towards increasing intervals between outbursts.

Figure 12. Upper panels: ULTRACAM photometry of ASASSN-14ei from four nights. Lower panel: Lomb-Scargle periodograms of the data shown in the upper panels, after first subtracting a three-term polynomial.

Trained spectra of some helium lines show marginally-visible S-waves from the bright spot (Figure 13). Each individual spectrum has been continuum- and mean-subtracted, in order to remove stationary components (including the accretion disc) and highlight the velocity-varying bright spot. The period of these S-waves is roughly consistent with the orbital period of \( \approx 40 \) min proposed previously. Unfortunately the bright spot is not strong enough to be detected by the cross-correlation method used for SDSS J1505+0659.

In order to explore the orbital period, Doppler maps were produced for a range of periods between 38 and 43 min. Each map was inspected visually in order to determine those maps in which the bright spot was most clearly visible. Such a qualitative approach is clearly not ideal; however, aliasing between the cadence of observations and the orbital period produces artefacts in the maps which are likely to confound quantitative measures such as entropy (Wang et al. 2017, 2018). Our preferred maps had orbital periods in the range of 41 to 42.5 min. In Figure 14 are shown Doppler maps produced using a period of 41.6 min.

The orbital periods preferred by this Doppler tomography method are slightly longer than the CRTS photometric orbital period of 40.0 min, and agree better with the proposed superhump period from VSNET of 41.63(3) min. It may be that the modulation reported in VSNET was in fact orbital in origin. Photometric signals at the orbital period can be seen in some systems during some stages of the outburst (eg. Isogai et al. 2019). However, with the current data we are unable to select between these possible orbital periods.

3.3 ASASSN-14nv

ASASSN-14nv (also known as V493 Gem) was discovered in superoutburst by ASAS-SN in 2014 December (Denisenko et al. 2014). These authors also discussed archival outburst detections from 1938 March (via the Heidelberg Astronomical Plates), 1991 March (via the Palomar Observatory Sky Survey II), and 2011 January (via the MASTER robotic network). The 2011 outburst is also visible in CRTS and PanSTARRS data (see Figure 1). During the 2014-15 outburst, photometric periods of 41.8 min (Stage A) and 41.0 min (Stage B) were reported by VSNET alert #18124\(^3\).

\(^3\) http://ooruri.kusastro.kyoto-u.ac.jp/mailarchive/vsnet-alert/18124
3.3.2 High-Speed Photometry

We observed ASASSN-14mv using ULTRASPEC on two consecutive nights during the 2014-15 superoutburst, and three nights in quiescence in 2017-18. These data are shown in Figure 15.

During outburst, strong modulations are seen on both nights, with periods of 40.2 min and 36.2 min. During quiescence, on two consecutive nights in 2018 February, a weaker but significant signal can be seen with periods of 40.2 min and 39.8 min. Apart from the January 05 signal, these periods are all consistent with the period detected in the AAVSO observations. The January 05 signal has a slightly shorter period, but a significant signal can be seen with periods of 40.9 ± 0.3 min, which is consistent with the superhump modulation reported by VSNET.
3.3.3 Spectroscopy

The mean spectrum of ASASSN-14mv is shown in Figure 4. It shows a typical AM CVn spectrum consisting of a series of He I and metal emission lines imposed on a blue continuum. The metals present include calcium, sodium, and nitrogen. The nitrogen emission is relatively strong when compared to ASASSN-14ei. The line profiles are narrow compared to other systems (Figure 5), suggesting a relatively face-on orbital inclination. Due to the long exposure times used, the orbital RV shifts of the binary are not measurable.

3.4 MOA 2010-BLG-087

MOA 2010-BLG-087 was detected during outburst in 2010 by the Microlensing Objects in Astrophysics (MOA) survey of the Galactic bulge. Follow-up photometry showed variability on a period of approximately 50 minutes, and a spectrum during outburst showed a series of helium lines, suggesting an AM CVn nature for the object (K. Horne, priv. comm.). The target is in a crowded region of sky, complicating follow-up. Figure 16 shows a finder chart, produced from a clipped-mean combination of ULTRACAM images with 1" seeing. Note that these images were taken during outburst, and so the target was unusually bright at this time.

3.4.1 Spectroscopy

The spectrum of MOA 2010-BLG-087 (Figure 3) is not typical for an AM CVn binary. Instead it appears similar to a K-type star. We have visually inspected the acquisition images taken prior to these data, and are reasonably confident that the correct target was observed. We suggest that the target is blended with a nearby K star in all ground-based observations to date. During outburst the AM CVn binary was the dominant source, while in quiescence the nearby star dominated.
3.4.2 High-Speed Photometry

We obtained photometry using ULTRACAM on three nights in 2010 April (Figure 17). The target was still at an elevated brightness, and the second night (April 22) coincided with an echo outburst that made the target three magnitudes brighter than April 21 and April 24. Modulations with periods of 49.9 min and 46.9 min are visible on April 22 and 24 respectively. Given the short observation window on April 24, the signal strengths between April 22 and 24 are comparable in terms of absolute flux, but the increased total brightness of the system on April 22 causes the signal to appear weaker on a magnitude scale.

For two unresolved stars where one is variable, there will be a correlation between total brightness and the centroid position of the blended object. We compared the x- and y-offsets in pixels of the target from the nearby comparison star (J2000 coordinates 18:08:35.3 − 26:29:14.7) on the nights of April 22 and 24. The y-offset was particularly strongly correlated with g’-band magnitude. Based on a Pearson’s R test, the two-tailed probabilities of such correlations occurring in an uncorrelated sample were < 10−28 and < 10−75, for April 22 and 24 respectively. We also found a correlation between g’-band magnitude and g’-r’ colour, giving two-tailed probabilities of < 10−18 and < 10−44. We therefore believe that the target AM CVn is blended with a nearby source.

In Gaia Data Release 2 (Gaia Collaboration et al. 2018), two objects are resolved at these coordinates with a separation of 2′ and magnitudes of G = 18.3 and 19.4. While it is tempting to suggest that these may be the two objects which are blended from the ground, we do not believe this to be the case, as a separation of 2′ should be easily resolved by ULTRACAM. We note that a nearby star is visible approximately 2′ north of the target in Figure 16.

MOA 2010-BLG-087 is the second AM CVn binary to have a co-aligned, late-type, main sequence star, after V407 Vul. For V407 Vul it is not known whether the co-aligned G-type star is a companion in a tertiary system or is aligned by coincidence, as the sky separation appears very small (0.027′; Barros et al. 2007).

3.5 CRTS J1028−0819

CRTS J1028−0819 (also known as CSS 090331) was discovered in outburst by CRTS in 2009. A Stage B superhump period of 54.9 ± 0.2 min was measured during outburst (Kato et al. 2009). Woudt et al. (2012) measured a photometric period during quiescence of 52.1 ± 0.6 min, which they suggest to be the orbital period. These photometric measurements suggest that CRTS J1028−0819 is the He CV with the shortest orbital period.

3.5.1 Long-term Lightcurve

The long-term lightcurve of CRTS J1028−0819 (Figure 1) shows a series of outbursts with an approximate recurrence time of 210 days. An AM CVn binary at this orbital period...
would be expected to have a very low accretion rate. As such the presence of any outbursts would be remarkable, and if they did occur the expected recurrence time would be significantly longer (Levitan et al. 2015). In terms of outbursts, it seems this He CV acts very unlike an AM CVn binary.

3.5.2 Spectroscopy

The mean spectrum of CRTS J1028−0819 is shown in Figure 2. It shows a series of hydrogen and helium emission lines, as well as emission from calcium, sodium, magnesium, and nitrogen. CRTS J1028−0819 shows He ii emission at 4686 Å.

Trailed spectra of the He line in CRTS J1028−0819 are shown in Figure 18. The system does not appear to show any bright spot S-wave, and no central spike is visible. In order to search for RV variations, the He line in each spectrum was cross-correlated with a Gaussian function, fixed such that its full-width at half-maximum was 1600 km/s. The resulting RV measurements are shown in Figure 19. A sinusoidal MCMC fit to these measurements produces a period of 53.4 ± 1.3 min, consistent with the photometric periods measured by Kato et al. (2009) and Woudt et al. (2012).

If we follow the interpretations of Kato et al. (2009) and Woudt et al. (2012) and take 52.1 min as the orbital period and 54.9 min as the stage B superhump period, Equation 2 gives $q = 0.25 ± 0.06$, which falls within the range of $q$ measurements for other He CVs.

3.6 V418 Ser

V418 Ser was classed as a dwarf nova following its outburst in 2004 (Rykoff et al. 2004) but few follow-up observations were performed at the time. Following a CRTS-detected outburst in 2014, photometry showed the system to have a superhump period of ≈ 64.3 min (Kato et al. 2015a). A spectrum reported by Garnavich et al. (2014) detected the presence of hydrogen.

3.6.1 Long-term Lightcurve

The long-term lightcurve of V418 Ser (Figure 1) shows a series of outbursts. The recurrence time is approximately 360 days, with a reasonable amount of scatter. As was the case for CRTS J1028−0819, the presence of outbursts marks a clear departure from the behaviour that would be expected of an AM CVn binary at this orbital period.

3.6.2 Spectroscopy

The mean FORS2 spectrum is shown in Figure 3. The system shows a series of emission lines from hydrogen and helium. Emission is also seen from magnesium. The Hβ line shows a notable absorption wing on its blue-ward side (the red-ward wing is hidden by nearby He i emission). The breadth of this absorption suggests it originates from the white dwarf photosphere. No absorption wings are visible around the helium lines.

Trailed spectra of V418 Ser show no visible S-wave from any bright spot or central spike, and no RV excursions were measurable for any emission line. The lack of any visible velocity excursions in V418 Ser suggests a low-mass donor star. This would imply a low mass-transfer rate, perhaps explaining the lack of any detectable bright spot in the spectroscopy. The visibility of photospheric hydrogen absorption may imply that the disc is unusually faint relative to the accreting white dwarf, which would also be consistent with a low accretion rate into the disc.

3.6.3 High-Speed Photometry

We obtained 2.5 hours of photometry of V418 Ser using ULTRACAM on 2018 April 15 (Figure 20). The lightcurve shows a feature resembling an orbital ‘hump’ (centred on 60 min and again on 125 min in Figure 20). Similar features are seen in a number of CVs and result from the non-isotropic nature of emission from the bright spot (eg. Wood et al. 1986) The presence of such a signal generally implies a relatively edge-on orbital inclination. However, if this signal does result from the bright spot, it is difficult to reconcile its strength with the weakness of the bright spot in spectroscopy.

The period of this modulation is 65.9 ± 0.6 min, where the uncertainty was estimated by fitting a sinusoid to the data. This is similar to the superhump period observed by Kato et al. (2015a), but slightly longer. As no uncertainty
4 DISCUSSION

4.1 Photometric Behaviour

As discussed in Section 3.2, the photometric behaviour of ASASSN-14ei is remarkable. The increased brightness and increased rate of outbursts following the 2014 superoutburst of ASASSN-14ei strongly suggest that the mass transfer rate increased in response to the 2014 superoutburst, perhaps due to heating of the donor star. The system seems even more remarkable when compared to ASASSN-14mv. The two systems appear to be similar in most measurable ways (the orbital periods and outburst magnitudes are similar, and both show the same echo outburst behaviour). Why then does ASASSN-14ei show an increase in mass transfer rate while ASASSN-14mv does not? This difference in behaviour may hint at some underlying difference in the nature of the two binaries, perhaps in the nature of the donor stars.

Leaving ASASSN-14ei aside, there is a stark difference between the outburst behaviour of the AM CVn binaries in this sample (which undergo outbursts rarely if at all) and that of the He CVs (which undergo outbursts with recurrence timescales on the order of 100s of days). The more frequent outbursts of the He CVs are likely due to higher accretion rates, resulting from higher mass donors.

4.2 Evolutionary Natures

One of the motivations behind this paper was to examine the possibility of an evolutionary link between AM CVn binaries and He CVs. A key signifier of the evolutionary history of these binaries is the donor mass and radius. In Figure 21 we show the donor masses and radii for all AM CVn binaries and He CVs with appropriate measurements. AM CVn measurements are taken from Green et al. (2018b, their Table 4 and references therein), and He CV measurements from the sources listed in Table 1. For the majority of these binaries only the mass ratio is known. For these binaries we assume $M_1 = 0.7 \pm 0.1 M_\odot$. Uncertainties are plotted diagonally due to the tight correlation between donor mass and radius, originating from the relationship between orbital period and donor mean density (Faulkner et al. 1972). By this relationship, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more massive, binaries with the shortest orbital periods will appear more mass...
We also estimate the mass ratio of CRTS J1028 in the bottom right of the figure, while the longest orbital periods would appear in the top left. On the same figure, we plot mass-radius evolutionary tracks for AM CVn binaries descended from the white dwarf donor channel (Deloye et al. 2007), the helium star donor channel (Yungelson 2008), and the evolved CV channel (Goliasch & Nelson 2015).

The two populations follow different distributions. He CVs are constrained to the 50-70 min orbital period range, but their distribution extent to much higher donor masses than AM CVn binaries of the same orbital period. There is, however, a region of mass-radius space in which low-mass He CV donors overlap with long-period AM CVn donors. The He CV CRTS J1122+1110 and the AM CVn binaries Gaia14aae, SDSS J0902+3819, and V396 Hya are all close to this region of overlap.

The q measurements made in this paper are highlighted in red in Figure 21. CRTS J1028−0819 appears to be towards the high-donor mass end of the distribution of He CVs, as would be expected based on its relatively high outburst rate. SDSS J1505+0659 appears to have a very similar donor to the next-longest-period AM CVn binary, V396 Hya. Looking at the five longest-period AM CVn binaries (five left-most in Figure 21), one could suggest a bifurcation in their radius distribution. SDSS J1505+0659, V396 Hya and GP Com all appear to have significantly smaller radii for their orbital period than Gaia14aae and SDSS J0902+3819, which are more inflated. Such a bifurcation is merely suggestive and is not detected to any significance given the uncertainties on these measurements.

## 5 CONCLUSIONS

We have presented a spectroscopic and photometric study of six accreting binary systems with orbital periods shorter than the period minimum for hydrogen-accreting CVs. Four of these binaries are of the AM CVn type, and two are He CVs. Four of these binaries have measured orbital periods, and four have measured superhump periods, either resulting from our observations or previously published. The binaries in this sample include the AM CVn binary with the longest known orbital period (SDSS J1505+0659 at 67.8 ± 2.2 min) and the He CV with the shortest known orbital period (CRTS J1028−0819 at 53.4 ± 1.3 min).

All but SDSS J1505+0659 have been detected in outburst. The outburst rates of the two He CVs are significantly higher than the outburst rates of the AM CVn binaries, likely due to higher-mass donor stars. Two of the AM CVn binaries, ASASSN-14ei and ASASSN-14mv, have notable outburst behaviour, with 12 and 10 echo outbursts respectively. The mass transfer rate of ASASSN-14ei appears to have increased substantially during the 2014 outburst, causing an increase in brightness and outburst rate. The system has since been gradually returning towards its quiescent state.

We measured the mass ratio for SDSS J1505+0659, which has a low-mass donor similar to that of V396 Vul. We also estimate the mass ratio of CRTS J1028−0819 based on previously-published photometric periods, and find that it has a high-mass donor, consistent with other He CV measurements. We note that there is some overlap between the regions of donor mass-radius space populated by AM CVn binaries and He CVs (Figure 21), but the systems studied in this work are not in that region of overlap.

## ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewer for their feedback. We would also like to thank Christian Knigge and Pier-Emmanuel Tremblay for helpful discussions and comments (during a viva examination!). We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research, includingFranz-Josef Hambusch, Gordon Myers, James Boardman, and David Cejudo Fernandez.

MJG acknowledges funding from STFC via studentship grant ST/N504506/1. MJG, TRM and DS are funded by STFC grant ST/P000495/1. VSD, SPL, ULTRACAM, and ULTRASPEC are funded by STFC via consolidated grant ST/J001589. SGP acknowledges support from the STFC via an Ernest Rutherford Fellowship.

This work is based in part on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programmes 085.D-0541, 095.D-0888, 0100.D-0425, 0101.D-0852, 0102.D-0060, and 0102.D-0953. Data were also obtained using the 2.4 m Thai National Telescope (TNT) operated by the National Astronomy Research Institute of Thailand (NARIT). Further data were obtained under proposal ITPS using the 4.2 m William Herschel Telescope (WHT), operated by the Isaac Newton Group of Telescopes.

This work made use of software packages SCIPY, NUMPY, ASTROPY, MATPLOTLIB, EMCEE, PAMELA, and MOLLY.

## REFERENCES

Abazajian K. N., et al., 2009, The Astrophysical Journal Supplement Series, 182, 543

Appenzeller I., et al., 1998, The Messenger, 94, 1

Armstrong E., Patterson J., Kemp J., 2012, Monthly Notices of the Royal Astronomical Society, 421, 2310

Augusteijn T., van Kerkwijk M. H., van Paradijs J., 1993, Astronomy and Astrophysics, 267, L55

Augusteijn T., van der Hoof F., de Jong J. A., van Paradijs J., 1996, Astronomy and Astrophysics, 311, 889

Barros S. C. C., et al., 2007, Monthly Notices of the Royal Astronomical Society, 374, 1334

Breedt E., 2015, Proceedings of The Golden Age of Cataclysmic Variables and Related Objects - III (Golden2015), p. 25

Breedt E., Gansicke B. T., Marsh T. R., Steeghs D., Drake A. J., Copperwheat C. M., 2012, Monthly Notices of the Royal Astronomical Society, 425, 2548

Breedt E., et al., 2014, Monthly Notices of the Royal Astronomical Society, 443, 3174

Breivik K., Kremer K., Bueno M., Larson S. L., Coughlin S., Kalogera V., 2018, The Astrophysical Journal Letters, 854, 1

Cannizzo J. K., Nelemans G., 2018, The Astrophysical Journal Letters, 854, 1

Cannizzo J. K., Nelemans G., 2015, The Astrophysical Journal, 803, 19

Cannizzo J. K., Ramsay G., 2019, The Astronomical Journal, 157, 130

Carter P. J., et al., 2013, Monthly Notices of the Royal Astronomical Society, 429, 2143

Carter P. J., et al., 2014, Monthly Notices of the Royal Astronomical Society, 439, 2848

MNRAS 000, 1–22 (2020)
Six Ultracompact Accreting Binaries

Chambers K. C., et al., 2016, preprint (arXiv:1612.05560)
Chochol D., et al., 2015, Acta Polytchnica CTU Proceedings, 2, 165
Copperwheat C. M., et al., 2011, Monthly Notices of the Royal Astronomical Society, 410, 1113
Deloye C. J., Tsam R. E., Winsdorffer C., Chabrier G., 2007, Monthly Notices of the Royal Astronomical Society, 381, 525
Denisenko D., et al., 2014, The Astronomer's Telegram, 6857, 1
Denisenok P. A., Ivanov V. V., 1987, Soviet Astronomy Letters, 13, 214
Dhillon V. S., et al., 2007, Monthly Notices of the Royal Astronomical Society, 378, 825
Dhillon V. S., et al., 2014, Monthly Notices of the Royal Astronomical Society, 444, 4009
Dhillon V. et al., 2018, in Proc. SPIE, p. 107020L (arXiv:1807.00557), doi:10.1117/12.2312041
Drake A. J., et al., 2009, Astrophysical Journal, 696, 870
Eggleton P. P., 1983, The Astrophysical Journal, 268, 368
Faulkner J., Flannery B. P., Warner B., 1972, The Astrophysical Journal, 175, L79
Fontaine G., et al., 2011, The Astrophysical Journal, 736, 92
Flemm-Mackay D., Hogg D. W., Lang D., Goodman J., 2013, Publications of the Astronomical Society of Paciﬁc, 125, 306
Gaia Collaboration T., et al., 2018, Astronomy & Astrophysics, 616, A1
Garnavich P., Littlefield C., Terndrup D., Adams S., 2014, The Astronomer’s Telescope, 6287
Goliasch J., Nelson L., 2015, The Astrophysical Journal, 809, 80
Goodman J., Weare J., 2010, Communications in Applied Mathematics and Computational Science, 5, 65
Green M. J., et al., 2018a, Monthly Notices of the Royal Astronomical Society, 476, 1663
Green M. J., et al., 2018b, Monthly Notices of the Royal Astronomical Society, 477, 5646
Green M. J., et al., 2019, Monthly Notices of the Royal Astronomical Society, 485, 1947
Hardy L. K., et al., 2017, Monthly Notices of the Royal Astronomical Society, 465, 4968
Hollier C., 2001, Cataclysmic Variable Stars. Springer, Berlin
Iben I. J., Tutukov A. V., 1987, The Astrophysical Journal, 313, 727
Imada A., Isogai K., Yanagisawa K., Kawai N., 2018, Publications of the Astronomical Society of Japan, 70, 79
Isogai K., Kato T., Monard B., Hambesch F.-J., Myers G., Starr P., Cook L. M., Nogami D., 2019, PASJ, 71, 48
Israel G. L., Panzera M. R., Campana S., Luzzi D., Covino S., Tagliferri G., Stella L., 1999, Astronomy and Astrophysics, 349, L1
Ivanova N., et al., 2013, Astronomy and Astrophysics Review, 21, 59
Kato T., Osaki Y., 2013, Publications of the Astronomical Society of Japan, 65, 115
Kato T., et al., 2004, Publications of the Astronomical Society of Japan, 56, S1
Kato T., et al., 2009, Publications of the Astronomical Society of Japan, 61, S205
Kato T., Hambsch F.-J., Monard B., 2015a, Publications of the Astronomical Society of Japan, 67, L2
Kato T., et al., 2015b, Publications of the Astronomical Society of Japan, 67, 105
Knigge C., 2006, Monthly Notices of the Royal Astronomical Society, 373, 484
Knigge C., Baraffe I., Patterson J., 2011, The Astrophysical Journal Supplement Series, 194, 28
Kochanek C. S., et al., 2017, Publications of the Astronomical Society of the Paciﬁc, 129, 104502
Kotko I., Lasota J.-P., Dubus G., Hameury J.-M., 2012, Astronomy and Astrophysics, 544, A13
Kremers K., Breivik K., Larson S. L., Kalogera V., 2017, The Astrophysical Journal, 846, 95
Kupfer T., Groot P. J., Levitan D., Steeghs D., Marsh T. R., Rutten R. G. M., Nelemans G., 2013, Monthly Notices of the Royal Astronomical Society, 432, 2048
Kupfer T., et al., 2015, Monthly Notices of the Royal Astronomical Society, 453, 483
Kupfer T., Steeghs D., Groot P. J., Marsh T. R., Nelemans G., Roelofs G. H. A., 2016, Monthly Notices of the Royal Astronomical Society, 457, 1828
Kupfer T., et al., 2018, Monthly Notices of the Royal Astronomical Society, 480, 302
Lasota J.-P., 2001, New Astronomy Reviews, 45, 449
Lawrence A., et al., 2007, Monthly Notices of the Royal Astronomical Society, 379, 1599
Levitan D., Groot P. J., Prince T. A., Kulkarni S. R., Laher R., Ofek E. O., Sesar B., Surace J., 2015, Monthly Notices of the Royal Astronomical Society, 446, 391
Littlefield C., et al., 2013, The Astronomical Journal, 145, 145
Lomb N. R., 1976, Astrophysics and Space Science, 39, 447
Longstaff F. S., Casewell S. L., Wynne G. A., Page K. L., Williams P. K. G., Braker I., Maxted P. F. L., 2019, MNRAS, 484, 2566
Marsh T., 2019, molly: 1D astronomical spectra analyzer (ascl:1907.012)
Marsh T. R., Horne K., 1988, Monthly Notices of the Royal Astronomical Society, 235, 269
Marsh T. R., Horne K., Schlegel E. M., Honeycutt R. K., Kaitchuck R. H., 1990, The Astrophysical Journal, 364, 637
Masli F. J., et al., 2019, Publications of the Astronomical Society of the Paciﬁc, 131, 018003
McAllister M., et al., 2019, Monthly Notices of the Royal Astronomical Society, 486, 5535
Meyer F., Meyer-Hofmeister E., 2015, PASJ, 67, 52
Moraes-Rueda L., Marsh T. R., Steeghs D., Unda-Sanzana E., Wood J. H., North R. C., 2003, Astronomy and Astrophysics, 405, 249
Morrissey P., et al., 2007, The Astrophysical Journal Supplement Series, 173, 682
Motch C., Haberl F., Guillout P., Pukull M., Reinsch K., Krautter J., 1996, Astronomy and Astrophysics, 307, 459
Mowchavi N., 1999, A&A, 350, 73
Nather R. E., Robinson E. L., Stover R. J., 1981, The Astrophysical Journal, 244, 269
Naylor T., 1998, Monthly Notices of the Royal Astronomical Society, 296, 389
Nelemans G., Yungelson L. R., Portegies Zwart S. F., 2004, Monthly Notices of the Royal Astronomical Society, 349, 181
Osaki Y., Meyer F., 2003, A&A, 401, 325
Osaki Y., Meyer F., 2004, A&A, 428, L17
Paczynski B., 1967, Acta Astronomica, 17, 287
Pala A. F., et al., 2020, MNRAS, 494, 3799
Patterson J., et al., 1998, Publications of the Astronomical Society of the Pacific, 110, 1290
Patterson J., et al., 2002, PASP, 114, 721
Patterson J., et al., 2005, The Publications of the Astronomical Society of the Paciﬁc, 117, 1204
Pearson K. J., 2007, Monthly Notices of the Royal Astronomical Society, 379, 183
Podsiadlowski P., Han Z., Rappaport S., 2003, Monthly Notices of the Royal Astronomical Society, 340, 1214
Prieto J. L., et al., 2014a, The Astronomer’s Telegram, 6475
Prieto J. L., et al., 2014b, The Astronomer’s Telegram, 6475
Ramsay G., et al., 2014, Monthly Notices of the Royal Astronomical Society, 438, 789
Ramsay G., et al., 2018, Astronomy and Astrophysics, 620, A141
Rau A., et al., 2009, Publications of the Astronomical Society of the Paciﬁc, 121, 1334
Roelofs G. H. A., Groot P. J., Nelemans G., Marsh T. R., Steeghs
Roelofs G. H. A., Rau A., Marsh T. R., Steeghs D., Groot P. J., Nelemans G., 2010, The Astrophysical Journal, 711, L138
Rui M. T., Rojo P. M., Garay G., Maza J., 2001, The Astrophysical Journal, 552, 679
Rykov E. S., et al., 2004, Information Bulletin on Variable Stars, 5559
Savonije G. J., de Kool M., van den Heuvel E. P. J., 1986, Astronomy and Astrophysics, 155, 51
Scargle J. D., 1982, The Astrophysical Journal, 263, 835
Shappee B. J., et al., 2014, The Astrophysical Journal, 788, 48
Smak J., 1981, Acta Astronomica, 31, 395
Solheim J.-E., 2010, Publications of the Astronomical Society of the Pacific, 122, 1133
Steeghs D., Marsh T. R., Barros S. C. C., Nelemans G., Groot P. J., Roelofs G. H. A., Ramsay G., Cropper M., 2006, The Astrophysical Journal, 649, 382
Szkody P., et al., 2005, The Astronomical Journal, 129, 2386
Thorstensen J. R., Fenton W. H., Patterson J. O., Kemp J., Krajci T., Baraffe I., 2002, The Astrophysical Journal, 567, L49
Uthas H., et al., 2011, Monthly Notices of the Royal Astronomical Society, 414, L85
VanderPlas J. T., 2018, The Astrophysical Journal Supplement Series, 236, 16
Vernet J., et al., 2011, Astronomy and Astrophysics, 536, A105
Wang L., Steeghs D., Casares J., Charles P. A., Muñoz-Darias T., Marsh T. R., Hynes R. I., O’Brien K., 2017, Monthly Notices of the Royal Astronomical Society, 466, 2261
Wang L., Steeghs D., Galloway D. K., Marsh T., Casares J., 2018, Monthly Notices of the Royal Astronomical Society, 478, 5174
Warner B., 1995, Cataclysmic Variable Stars. Cambridge University Press, Cambridge
Wood J., Horne K., Berriman G., Wade R., O’Donoghue D., Warner B., 1986, Monthly Notices of the Royal Astronomical Society, 219, 629
Woudt P. A., Warner B., de Búdor, 2011, The Astronomer’s Telegram, 3705
Woudt P. A., Warner B., de Búdor, Macfarlane S., Schuch M. P. E., Zietsman E., 2012, Monthly Notices of the Royal Astronomical Society, 421, 2414
Wright E. L., et al., 2010, The Astronomical Journal, 140, 1868
Yunzhe L. R., 2008, Astronomy Letters, 34, 620

This paper has been typeset from a TeX/LaTeX file prepared by the author.