

A speckle-imaging search for close triple companions of cataclysmic binaries

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ABSTRACT

The orbital periods of most eclipsing cataclysmic binaries are not undergoing linear secular decreases of order a few parts per billion as expected from simple theory. Instead, they show several parts per million increases and decreases on time-scales of years to decades, ascribed to magnetic effects in their donors, triple companions, or both. To directly test the triple companion hypothesis, we carried out a speckle-imaging survey of six of the nearest and brightest cataclysmic variables. We found no main-sequence companions earlier than spectral types M4V in the separation range ~ 0.02 –1.2 arcsec, corresponding to projected linear separations of ~ 2 –100 au, and periods of ~ 3 –1000 yr. We conclude that main-sequence triple companions to cataclysmic variables are not very common, but cannot rule out the presence of the faintest M dwarfs or close brown dwarf companions.

Key words: techniques: high angular resolution – binaries: close – stars: dwarf novae – novae, cataclysmic variables.

1 INTRODUCTION

Almost all cataclysmic variables (CVs) comprised red dwarfs (RD) or red giants transferring hydrogen-rich matter on to the surfaces of their white dwarf (WD) companions (Warner 1995). Mass transfer in these binaries (Walker 1954; Kraft 1962, 1964) drives a rich variety of phenomena. The most spectacular of these include the reasonably well understood accretion-powered outbursts of dwarf novae (Osaki 1974; Dubus, Otulakowska-Hypka & Lasota 2018) and the thermonuclear-powered eruptions of classical novae (Starrfield et al. 1972; Prialnik, Shara & Shaviv 1978).

Until the advent of large CCDs and large-area synoptic studies, many CVs (other than novae) were found because of their strong emission lines (Stephenson & Sanduleak 1977) or very blue colours (Green, Schmidt & Liebert 1986). Most CVs are now detected via their outbursts in wide-area synoptic surveys (Drake et al. 2014; Mróz et al. 2015a, b).

Five to ten erupting Galactic classical novae are usually detected in any given year... often by amateur astronomers. A germinal wide area, infrared survey of the Milky Way has recently shown that the Galactic nova eruption rate is 46 ± 12 novae yr⁻¹ (De et al. 2021). This confirms that ~ 80 –90 per cent of Galactic novae have been missed over the past century because they are distant and reddened. Deep, high cadence all-sky visible-light surveys, and infrared surveys will greatly increase the outbursting Galactic nova and dwarf nova detection rates in the coming decade.

GAIA confirms that the closest known of all CVs (WZ Sge) is 43 pc distant, consistent with a space density of CVs that is $\sim 5 \times 10^{-5}$ pc⁻³ (Pala et al. 2020), *unless* most CVs ‘hibernate’ as detached RD-white binaries during most of the time between successive nova eruptions (Shara et al. 1986; Hillman, Shara, Prialnik & Kovetz 2020). This *GAIA*-based space density is \sim four orders of magnitude lower than that of main-sequence stars near the Sun. Thus, in zeroth approximation, 1 star in 10 000 near the Sun is currently a mass-transferring CV.

1.1 CV orbital periods

Other phenomena associated with CVs are much less well-understood. As expected for a collection of binaries with randomly oriented orbital planes, ~ 10 –15 per cent of all CVs are deeply eclipsing. Individual eclipsing systems’ orbital periods P can be measured, over a baseline of \sim a decade, with precisions of 1 part in 10^7 . The orbital period distributions of all subtypes of CVs, and their various subclasses, are important tests of evolutionary models of CVs. Population synthesis and binary-evolution codes can be coupled with angular momentum loss prescriptions (Schreiber, Zorotovic & Wijnen 2016) to produce predictions of the orbital period distributions of CVs (Howell, Nelson & Rappaport 2001; Goliašch & Nelson 2015; Schreiber et al. 2016). The models’ predictions are poor matches to the observed orbital period distributions of all CVs (Schreiber et al. 2016), dwarf novae (Knigge, Baraffe & Patterson 2011), and classical novae (Fuentes-Morales et al. 2021). In particular, the ratio of short to long-period CVs, the observed strong peak of novae in the 3–4 h period range (Fuentes-Morales et al. 2021) and the shortage of dwarf novae in the 2–4 h period

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range (Knigge et al. 2011) are seriously discrepant with models' predictions.

1.2 CVs' dP/dt

The rates of change of CV orbital periods dP/dt are also not well-understood. CVs' P are predicted to be secularly decreasing because the underlying binaries are shedding angular momentum (Howell et al. 2001; Knigge et al. 2011) via their secondaries' winds (Verbunt & Zwaan 1981) and gravitational radiation (Paczynski & Sienkiewicz 1981). CVs born with $P \sim 10$ h should reach $P \sim 3$ h in ~ 1 Gyr (Knigge et al. 2011; Hillman, Shara, Prialnik & Kovetz 2020). This corresponds to dP/dt of order -10^{-11} cycles d^{-1} , or a few parts per billion (ppb) yr^{-1} . Contrary to expectations, CVs P that have been monitored for decades show orbital period decreases, increases, and cyclical variations. Borges et al. (2008) lists 14 well-known eclipsing CVs which display orbital period modulations with amplitudes as large as 7.9 parts per million (ppm) on time-scales of 5–35 yr. Updates and new additions to this list are given by Pilarčik et al. (2012), Boyd (2012), Bruch (2014), Pilarčik et al. (2018), Patterson et al. (2018), and (Schaefer 2020). Borges et al. (2008) adds '...there (are) presently no CVs with well sampled and precise ($O-C$) diagrams covering more than a decade of observations that do not show cyclical period changes'. The amplitudes and oscillatory frequencies of the dP/dt of all classes of CVs show no clearcut patterns.

1.3 Explaining dP/dt

1.3.1 Starspots

One possible explanation for the modulations of CVs' periods is magnetic activity cycles and star-spots in their hydrogen-rich donors (Applegate 1992; Livio & Pringle 1994). These can greatly vary mass and angular momentum transfer rates on time-scales of years. Tomographic studies provide support for this hypothesis, showing large star-spots on the secondaries of BV Cen, V426 Oph, and SS Cyg (Watson et al. 2007a, b; Hill 2016).

1.3.2 Triple companions

A second (and non-exclusionary) explanation is that CVs may display positive or oscillatory dP/dt because they are in triple-star systems. The distant companion of a CV with years-to-centuries long orbits would periodically displace the center of mass of the CV to approach and then recede from Earth. The variable light travel time to a CV in a triple or multiple-star system would yield 'early' and 'late' eclipses, and variations in dP/dt . Triple companions at linear separations from CVs' centers of mass of 3, 10, and 30 au would experience orbital periods of ~ 5 , 30, and 160 yr, respectively.

Triple companions are not as far-fetched as they might seem at first glance – there are 3 triple-star systems (and 7 binaries) amongst the 21 star systems closest to Earth (Henry et al. 2018). Even higher order multiples are remarkably common (Tokovinin 2018). Five of the nine nearest triple or higher multiple-star systems (GJ 570C, GJ 663, GJ 644, G 041–014, and LP 771–095) contain tertiary components certain or possibly of spectral type M4V or earlier,¹ corresponding to our observational detection limits (see below).

¹<http://www.astro.gsu.edu/RECONS/TOP100.posted.htm>

Most current WDs in CVs must have been red giants with radii $\geq 1-3$ au which engulfed their companions in the past (Meyer & Meyer-Hofmeister 1979; Paczynski & Sienkiewicz 1981; Law & Ritter 1983). Current triple companions to CVs that were sufficiently distant from the common envelope binary (≥ 3 au from the red giant) to have avoided engulfment then would have spiraled out to distances $\sim 2-3$ times larger due to mass loss from the inner, pre-CV binary. Closer in triple companions could have stayed at \sim the same separation, or even moved closer in if they, too, were engulfed by the expanding atmosphere of the red giant. Theoretical considerations (Leigh et al. 2020) and numerical simulations of the complex evolution of triple stars (Hamers et al. 2021) make it clear that post common envelope binaries (PCEB) and CVs' triple companions of all masses (less than the initially most massive star in the triple system) and separations are possible.

1.3.3 CV, PCEB, and EL CVn triples

Examples of CVs suggested to be triple on the basis of variable dP/dt include CH Cyg (Skopal et al. 1998), VY Scl (Martínez-Pais et al. 2000), V542 Cyg (Thorstensen, Peters & Skinner 2010), FS Aur (Chavez et al. 2012, 2020), V2051 Oph (Qian et al. 2015), U Gem (Warner 1988; Dai & Qian 2009), and EM Cyg (Liu et al. 2021). The masses of companions required to produce the observed dP/dt range from those of giant planets, through brown dwarfs, up to $\sim 0.8 M_{\odot}$.

Eclipsing PCEB that will become CVs also display large departures from expected mid-eclipse times. (Zorotovic & Schreiber 2013) provided a comprehensive overview of eclipse timing variations in PCEB. They found that a remarkable ~ 90 per cent of PCEBs exhibit period variations. If these variations are due to tertiary companions, their masses are likely in the planetary or brown dwarf mass range. The best-studied example to date is NN Ser (Parsons et al. 2010). Beuermann et al. (2010) found excellent agreement with the observed period changes of NN Ser via two additional bodies with masses several times that of Jupiter superposed on the linear ephemeris of the binary. Remarkably, Marsh et al. (2014) found that the two-planet model correctly *predicted* a progressive lag in eclipse times of 36 s that set in since 2010 compared to the previous 8 yr of precise times.

Two PCEB binaries that are particularly instructive are Wolf 1130 and V471 Tau. On the one hand, there is no doubt of the triple nature of the pre-CV Wolf 1130 (Mace et al. 2018), located just 16.6 pc distant from Earth. Wolf 1130 comprised a T8 brown dwarf ~ 3000 au from, and in orbit around an M subdwarf – One WD, which is itself in a 0.4967 day orbit. In contrast, the nearby PCEB, pre-CV binary V471 Tau has also often been cited as a triple-star candidate (Kundra & Hric 2011). However, recently very sensitive observations have ruled out even a brown dwarf companion (Hardy et al. 2015) with a high degree of confidence.

The EL CVn eclipsing binaries, which are closely related to PCEBs, contain an A- or F-type star and a very low mass ($\sim 0.2 M_{\odot}$) pre-Helium WD. The low pre-WD masses mean that EL CVn stars must form from dynamically stable-mass transfer when the more massive star of the initial main-sequence binary was at the end of its main-sequence lifetime, or had just entered the sub giant branch (Chen et al. 2017), with the orbital period of the progenitor binary < 3 days. Virtually all close main-sequence stars with orbital periods < 3 days are known to be the inner binaries of hierarchical triple systems (Tokovinin et al. 2006). Lagos et al. (2020) examined five EL CVns in detail and found that all had nearby companions, consistent with K–M dwarfs.

Table 1. Gemini speckle observations of six CVs.

Object	CV type	V_{\min} (mag)	Period (min)	Dist. (pc)	Date observed	Obs. time (min)	λ_{filter}	Δ mag @ 1 arcsec
IX Vel	NL	10.1	279.25	90.6 ± 0.2	2020-Nov-29	30	653/832	6.5/8.2
AE Aqr	IP	10.4	592.78	91.2 ± 0.5	2020-Jun-13	20	466/716	5.0/8.4
U Gem	UG	8.5	254.74	93.4 ± 0.3	2020-Feb-17	35	466/716	4.5/5.9
SS Cyg	UG	8.0	396.19	114.6 ± 0.6	2020-Jun-15	30	466/716	4.8/7.8
V884 Her	AM	12.8	113.01	115.1 ± 0.3	2020-Jun-11	8	466/716	4.9/5.1
AH Her	UGZ	10.8	371.69	324.3 ± 3.3	2020-Feb-18	22	466/716	3.7/5.7

Notes. Column 2: NL = novalike variable; IP = intermediate polar; UG = U Geminorum-type dwarf nova;

AM = AM Herculis CV = polar; UGZ = Z Camelopardalis-type dwarf nova.

Column 3: CV's brightest V magnitude.

Column 8: Filter central wavelength (nm).

1.4 Motivation and outline of this study

Claims of triple companions to most CVs and PCEBs will require decades to centuries to resolve if the only evidence remains eclipse timings. The recent availability of new, very high resolution imaging facilities capable of detecting companions 5 (10) mag fainter than CV binaries at separations as small as 17 (1000) mas prompted us to search for such companions amongst the closest and brightest known CVs. These angular separations correspond to linear separations of putative triple companions that are relevant for CV P changes on interesting time-scales (see Section 3).

In Section 2, we briefly describe the speckle cameras, targets, and observations of this study. In Section 3, we show the results of our observations, placing stringent limits on optical companions to six of the brightest and closest known CVs. We briefly summarize our results in Section 4.

2 TARGETS AND OBSERVATIONS

In this first exploratory study, we observed six of the closest and best-studied CVs. They and their CV subtypes are IX Velorum (the closest novalike variable), AE Aquarii (an Intermediate Polar in a ‘propeller’ binary), U Geminorum (the prototypical U Gem-type dwarf nova, and suggested to have a triple companion (Dai & Qian 2009)), SS Cygni (the brightest dwarf nova), V884 Her (one of the closest highly magnetic-WD Polars), and AH Herculis (one of the closest Z Cam-type CVs). In Table 1, we list these six targets, their CV subtypes, orbital periods, *GAI*A-determined distances, the dates of observation, integration time, the central wavelengths of the filters used to observe each target, and lower limits in the blue and red passbands on how much fainter any undetected companions must be at 1.2 arcsec from the CVs.

The observations were carried out with the twin speckle cameras Zorro and ‘Alopeke located at the twin 8-m Gemini-S and Gemini-N telescopes, at Cerro Pachon, Chile, and Mauna Kea, Hawaii, respectively. ‘Alopeke and Zorro are dual-channel imagers using two electron-multiplying CCDs as the detectors. Each provides simultaneous two-colour, diffraction-limited optical imaging (FWHM ~ 0.017 arcsec at 550 nm) of targets as faint as $V \sim 17$ over a 6.7 arcsec field of view. Each camera can also resolve wider companions (0.2–1.5 arcsec) with very large magnitude differences (up to 8–10 mag). Each has filter wheels providing bandpass limited observations. See Scott et al. (2018) for a detailed description of the instruments and their filters, as well as the ‘Alopeke-Zorro Web pages.² Each observation comprised multiple sets of 1000 exposures of 60 ms each, as well as calibration observations. The data reductions are

described in Horch et al. (2012) and the final data products are discussed in Howell et al. (2011).

3 RESULTS

The results of all observations are shown in Fig. 1. The red and blue curves in each figure correspond to the two filters used in each observation. They measure the contrast limits Δm achieved in magnitudes below the primary target. The reconstructed images, covering a ~ 1.5 arcsec \times 1.5 arcsec region centered on each CV are also shown. In several cases (most notably AE Aqr and IX Vel), the surrounding background appears asymmetric and/or ‘ringlike’. These ‘features’ are at the noise limit of the images, and are not real.

The key result of this paper is that no close, main-sequence triple companions (earlier than spectral type M4V) to any of the six observed target CVs were detected in the separation range 0.02–1.2 arcsec. Our observations are more sensitive in the redder filter, where very close companions ($\rho < 0.1$ arcsec) within 3–5 mag of the CVs are excluded. Farther out (0.1 arcsec $< \rho < 1.2$ arcsec), companions 5–8 mag fainter than the CVs would have been detected.

Five of the six observed CVs (IX Vel, AE Aqr, SS Cyg, U Gem, and V884 Her) are all located at about the same distance from Earth: 100^{+15}_{-10} pc. At 100 pc the angular separations 0.02, 0.1, and 0.3 arcsec correspond to projected linear separations of 2, 10, and 30 au, respectively. Triple companions at those distances would experience orbital periods $\sim 3, 30,$ and 160 yr, respectively, similar to those noted for putative CV triple companions in the introduction.

We conclude by noting that our observations are *not* sensitive to brown dwarfs or the faintest M dwarfs; high-resolution infrared techniques will be needed to search for such companions to CVs.

4 SUMMARY AND CONCLUSIONS

Tertiary companions from planets to brown dwarfs to RD are known or suspected to exist around close binaries. If present, they cause orbital period variations of the inner binary. Such variations are observed for many CVs, though they might be due to other causes. To test whether close stellar companions to CVs might be common, we carried out visible-light speckle observations of six of the nearest/brightest known CVs to try to image nearby triple companions.

No companions were found in the angular separation range ~ 0.02 –1.2 arcsec, corresponding to physical separations of ~ 2 –100 au, and orbital periods of triple companions of ~ 3 –1000 yr. While far from definitive, this small survey demonstrates that main-sequence triple companions to CVs, of spectral types earlier than M4V, are not common. Our survey is not sensitive to the faintest M dwarfs or brown dwarfs, where high-resolution, near-infrared techniques must be employed.

²<https://www.gemini.edu/instrumentation/alopeke-zorro>

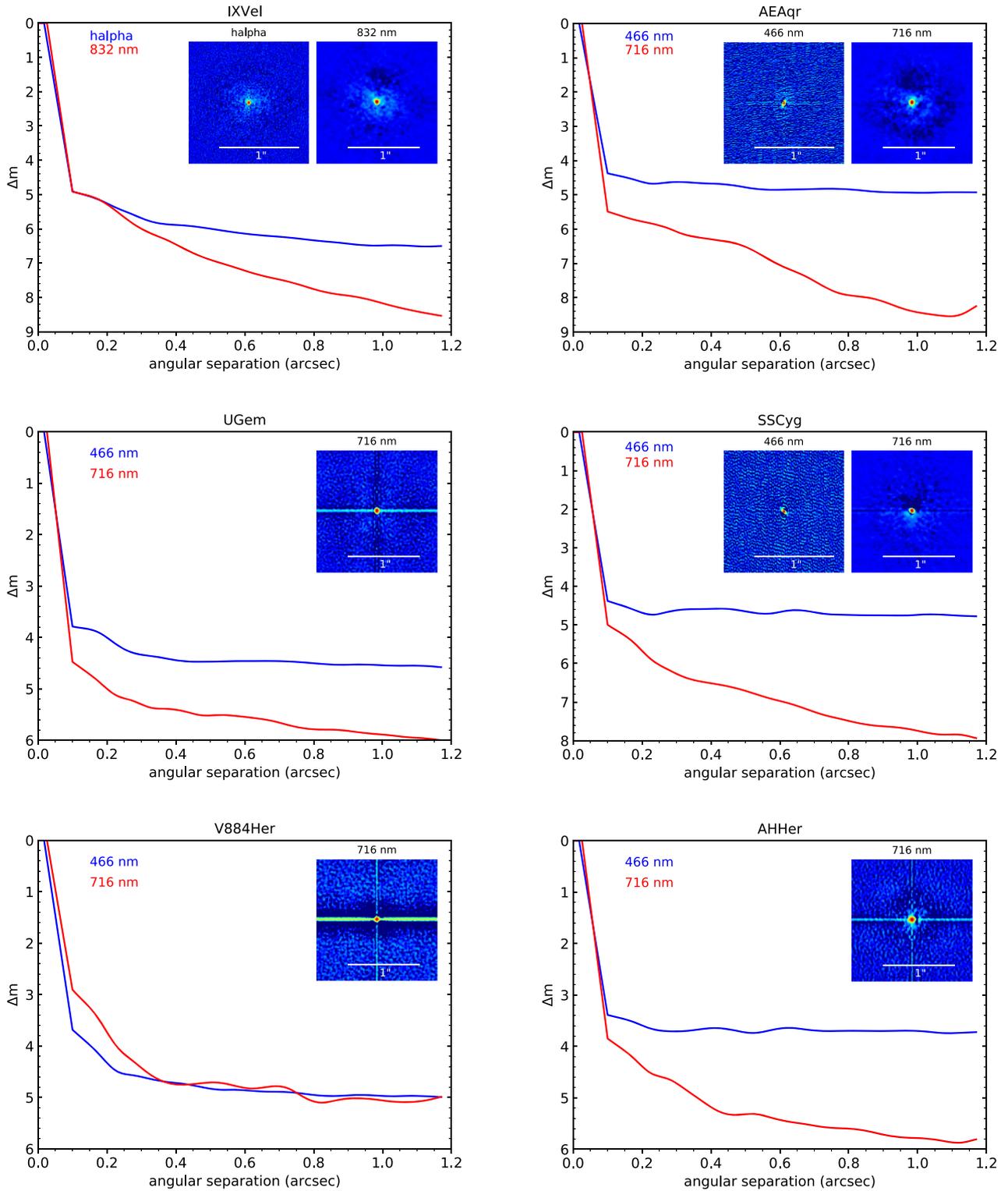


Figure 1. The reconstructed images and differential magnitude detection limits Δm of the six CVs (left to right, top to bottom): IX Vel, AE Aqr, U Gem, SS Cyg, V884 Her, and AH Her. There is no indication of any companion within 100 mas of any of the six stars that is within ~ 4 mag of the CV in either the blue (466 nm) or the red ($H\alpha$ or 716 nm) narrowband filters, respectively. Neither is any companion detected within ~ 4 –6 mag (blue filter) nor 5–8 mag (red filter) out to 1.2 arcsec from any of the CVs. See the text for details.

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5 DATA AVAILABILITY STATEMENT

The data underlying this article will be shared on reasonable request to the corresponding author. The raw speckle data are also available on the Gemini archive.

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