Eclipse time variations & the continued search for companions to short-period eclipsing binary systems

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Eclipse time variations have been detected in a number of post-common envelope binary systems consisting of a subdwarf B star or white dwarf primary star, and cool M-type or brown dwarf secondary. In this paper we consider circumbinary hypotheses of two sdB systems, HS 0705+6700 (also known as V470 Cam) and NSVS 14256825, and one white dwarf system, NN Ser. In addition, and for comparison purposes, we investigate the eclipse time variations of the low-mass binary system NSVS 01286630 with its stellar circumbinary companion. All four eclipsing systems have claims of circumbinary objects with computed physical and orbital parameters. We report 108 new observations of minima for these systems obtained between 2017 May and 2019 September and combining these with all published data, we investigate how well the published circumbinary object hypotheses fit with our new data. The new data have shown departure from early predictions for three of the four systems, but it is premature to conclude that these results rule out the presence of circumbinary objects. There is also the possibility (but with no observational proof so far) of detecting close-in transiting circumbinary objects around the systems, but these are likely to have periods of days rather than years.

Introduction

From observations of eclipse time variations (ETVs), many claims have been made of the detection of circumbinary objects orbiting subdwarf B (sdB) binary systems, members of the HW Vir family, and binary systems where the primary has evolved into a white dwarf. Typically, these systems have a very hot primary component with temperatures in excess of 30,000K, and a secondary M dwarf or brown dwarf companion with temperatures of 3,500K or less. The separation between the two components is usually less than one solar radius, causing the secondary to be heavily irradiated by the primary star. This gives rise to significant amounts of reflected energy from the secondary.

An HW Vir-type system's compact structure, short periods and large temperature differences between the two components give rise to short and well-defined primary eclipses, allowing times of minima to be determined with high precision. These systems have undergone a post-common envelope binary (PCEB) evolution, as described in the Appendix, with many showing apparent periodic variations in their eclipse timings. An overview is provided by Zorotovic & Schreiber (2013) and Lohr *et al*. (2014).[1,2]

In this paper we consider three PCEB systems – HS 0705+6700, NSVS 14256825, and NN Ser – as well as one evolving into a W UMa-type of system: NSVS 01286630. Claims have been made for the presence of circumbinary objects, with calculated parameters, orbiting all four systems. Of all the putative objects discovered through ETVs, those around NN Ser were thought to be amongst the most compelling because of the high quality of the data and because its main-sequence companion is a late-M star, which restricts the possibility of other causes for period changes, for example magnetic coupling. With our new observations we investigated the periodic variation in the position of the barycentres of these four systems, to see if they fit with previous predictions of circumbinary orbits. While the NN Ser and NSVS 14256825 systems' planets are listed in various international databases, *e.g.* NASA Exoplanet Archive, neither of the other two systems have this level of recognition, calling into question their proposed circumbinary hypotheses.

While the more exciting explanation of attributing these period variations to the presence of planets or brown dwarfs orbiting the systems has been a popular consideration, other factors could also explain their cyclical behaviour (see last paragraph of the 'Observing method & data reduction' section which follows). Other claims of circumbinary objects are for close eclipsing binary systems of the W UMa-type or binary systems evolving to a W UMa once their Roche lobes are filled, such as NSVS 01286630, the fourth system described herein.

We discuss the possibility that these other factors could explain the cyclical behaviour of these four systems, attributed in the literature to circumbinary objects. We note that two of the systems

Table 1. Summary of the objects observed between 2017 May & 2019 September, with a total of 105 times of primary minima & three of secondary minima

						New observations		
Object	*RA (J2000)*	*Dec. (J2000)*	*Period (d)*	*Distance (pc)*	*Mag.*	*Primary*	*Secondary*	*Period*
HS 0705+6700	07 10 42.06	+66 55 43.52	0.095646609	1001	14.60 (R)	40	0	2017 Oct – 2019 Sep
NN Ser	15 52 56.13	+12 54 44.68	0.130080142	522	16.51 (V)	16	0	2017 May – 2019 Aug
NSVS 01286630	18 47 08.58	+78 42 29.34	0.383927870	324	13.09 (V)	20	2	2018 Jul – 2019 Sep
NSVS 14256825	20 20 00.48	+04 37 56.49	0.110374168	838	13.34 (R)	29	1	2017 Sep – 2019 Sep

Table 2. Summary of key parameters of the binary systems observed

Object	M_1 ($M_\odot$)	M_2 ($M_\odot$)	$Teff_1$ (K)	$Teff_2$ (K)	Sp. Type M_1	Sp. Type M_2	a ($R_\odot$)	i (°)	Reference
HS 0705+6700	0.48	0.13	29600	2900	sdB	M4/M5	0.81	84.4	Drechsel *et al.* (2001)
NN Ser	0.57	0.12	57000	2950	WD	M4[1]	0.95	84.6	Brinkworth *et al.* (2008)
NSVS 01286630	0.68	0.72	4140	4290			0.72	89.0	Coughlin & Shaw (2007)
NSVS 14256825	0.46	0.21	35250	3500	sdB	M5/M7	0.74	82.5	Kilkenny & Koen (2012)

Notes: The spectral types for these systems are not clearly defined, being indirectly determined from light curve parameters which themselves can be poorly constrained. [1]Bours *et al.* (2016).

(HS 0705+6700 and NSVS 14256825) have been included in our recent study of seven short-period eclipsing binaries (Pulley *et al.*, 2018).[3] As will be seen, our recent observations, which cover two additional seasons, support the conclusion of further deviations from previous predictions.

In this paper we present the ETVs exhibited by four eclipsing binary systems at somewhat different stages of binary evolution, and we analyse the results in the context of circumbinary planet hypotheses. The analysis is preceded by a brief historical review of the hypotheses presented by earlier observers. The four systems studied are listed with their parameters in Tables 1 & 2.

Table 3. Telescopes and Minor Planet Centre (MPC) codes used for the measurements reported

Telescope/Observatory	MPC Code	Reference (see Table 4)
0.51m Gemini, Univ. of Iowa	857	1
0.51m SSON, Australia	Q65	2
0.5m iTelescope T11, New Mexico	H06	3
0.32m iTelescope T18, Nerpio	I86	4
0.43m iTelescope T21, New Mexico	H06	5
0.61m iTelescope T24, California	U69	6
0.7m iTelescope T27, Warrumbungle	Q65	7
2m, LCO Faulkes South	E10	8
2m, LCO Faulkes North	F65	9
0.28m, Greenmoor Obs., Oxfordshire	Z54	10
0.36m, Astrognosis Obs., Essex	K01	11
0.2m, Woodland Obs.,W. Sussex	–	12
0.23m, Ham Obs., W. Sussex	–	13

Observing method & data reduction

In Table 3 we list the telescopes used to obtain the new data and in Table 4 we report 108 new observations of the four eclipsing binary systems between 2017 May and 2019 September. The effects of atmospheric extinction were minimised by making all observations at altitudes greater than 40°. All images were calibrated using dark, flat, and bias frames, then analysed with *Maxim DL* or *Astroart*.[4,5] The source flux was determined with aperture photometry using a constant aperture for all images, and the radius scaled according to the full width at half maximum (FWHM). Variations in observing conditions were accounted for by determining the flux relative to an ensemble of comparison stars in the field of view. The apparent magnitude of the target was derived from those of the comparison stars and its average magnitude calculated by the software.

This was done as follows. Firstly, the same comparison stars were used for each image. Using the average derived magnitude of the target from each comparison star and the standard deviation of the average, the final value for the target was obtained for each frame. The magnitudes of the comparison stars were chosen, appropriate to the filter being used. The comparison stars' catalogue magnitudes for the various filters were taken from the American Association of Variable Star Observers (AAVSO) Photometric All Sky Survey (APASS) catalogue.[6] These were similar to the target magnitudes and, whenever possible, had similar colour indices to the target stars. Because the APASS catalogue does not include the R pass band, in the few cases where observations were taken with the R filter a conversion formula recommended by the AAVSO was used to transform the catalogue's Sloan r′ magnitudes to the corresponding R magnitudes. Whether observations were performed with or without filters, check stars were used to ensure that there was no variability in the reference star selected.

All of our new mid-image timings used in this analysis were first converted to Barycentric Julian Date Dynamical Time (BJD_TDB) using the Ohio State University or the *Astropy* time utilities.[7,8] Computer clocks were synchronised with external atomic clocks during the imaging process. Times of minima were calculated using the Kwee & van Woerden (1956) methodology and implemented with *Peranso* light curve analysis software.[9,10] Our new timings were combined with previously published times of minima and, where appropriate, the historic times were converted to BJD_TDB. Where a new linear or quadratic ephemeris was calculated, only observed primary minima data were used. The differences between the observed and calculated times of minima were used to infer potential internal or external influences on the binary pair, for example: angular momentum loss through magnetic braking or the emission of gravitational waves; angular momentum redistribution through Applegate-type mechanisms; the apparent changing of the binary period through the presence of a circumbinary object; or apsidal motion (see for example Brinkworth *et al.* (2006); Bours *et al.* (2016) and references therein).[11,12]

Analysis of eclipse timings

HS 0705+6700 (V470 Cam)

Background

HS 0705+6700 is a magnitude 14.6 sdB star, first identified in the Hamburg Schmidt Quasar Survey. Subsequent observations by Drechsel *et al.* (2001) confirmed this object as a member of a short-period, 2.3h PCEB system.[13] Light curve analysis indicated that the secondary companion was a low-mass red dwarf star with mass and radius of 0.13$M_\odot$ and 0.19$R_\odot$, respectively. Niarchos *et al.* (2003) confirmed this structure, but observations by Qian *et al.* (2009) suggested that the binary period had a superimposed cyclical component with a period of 7.15y and light travel time (LTT) amplitude of 92.4s.[14,15] The LTT effect in eclipsing binaries occurs because the distance to the observer varies due to the reflex motion of circumbinary companions moving around the barycentre of multiple systems. Qian's analysis ruled out period change due to apsidal motion, magnetic coupling (Applegate effect) and angular momentum loss; they concluded that the most likely cause of the observed period change was the presence of a brown dwarf circumbinary companion of mass 39.5M$_J$. Further observations and analysis by Qian *et al.* (2010, 2013),[16,17] Camurdan *et al*. (2012) and Beuermann *et al*. (2012) strengthen this prediction by providing some 15 years of data spanning ~1.7 circumbinary periods.[18,19] Qian's revised analysis suggested a brown dwarf circumbinary companion of mass 32M$_J$ and with a period of 8.87y.

Although observations by Pulley *et al.* (2015) initially confirmed these findings, they noted in their addendum that data post-2015 February indicated a departure from the proposed circumbinary model.[20] This departure was confirmed by Pulley *et al*. (2018), bringing into question the circumbinary brown dwarf prediction.[3]

Further data and analysis by Bogensberger *et al.* (2017), using a linear ephemeris, resurrected the circumbinary brown dwarf prediction but with a significantly longer period of 11.8y and orbital eccentricity of 0.38.[21]

New observations & ephemeris

We provide 40 new times of minima taken from observations made between 2017 October and 2019 September. As shown by Qian *et al.* (2013), the quadratic ephemeris provides a better fit to the data than the corresponding linear ephemeris through to 2015 March.[17] Utilising the quadratic ephemeris of Pulley *et al*. (2018),[3] Equation [1] below, the plot of (O–C) residuals is shown in Figure 1, where the red line represents the predicted (O–C) residuals incorporating the circumbinary companion.

$$T_{\text{min, BJD}} = 2451822.76155(5) + 0.095646609(4)E + 5.5(9)\times10^{-13}E^2 + \tau \qquad [1]$$

where E is the number of binary periods measured from the reference epoch of 2451822.76155 and τ is the cyclical LTT effect of a putative circumbinary object, given by:

$$\tau = \frac{a_{12}\sin i}{c}\left[(1-e^2)\,\frac{\sin(v+w)}{1+e\cos v} + e\sin w\right] \qquad [2]$$

and $(a_{12}\sin i)/c$ is the LTT amplitude of 88.1s; e is the circumbinary component orbital eccentricity of 0.03; w, the angle of periastron, is 0.119rad and v is the true anomaly, determined from the time at periastron of 2449484.0d and circumbinary period of 8.55y.

Our new data ($E > 65{,}115$) are not consistent with the findings of Bogensberger *et al*., but are consistent with our earlier findings, confirming the departure from the pre-2015 circumbinary prediction of Qian, Camurdan, Beuermann and Bogensberger. Using the post-2015 March data only, we compute a new linear ephemeris:

$$T_{\text{min, BJD}} = 2451822.75657(16) + 0.095646732(3)E + \tau \qquad [3]$$

The (O–C) residuals, based on Equation 3, are shown in Figure 2 where there is seen to be a quadratic trend. A comparison of the linear and quadratic fits for these latter data shows that the reduced χ^2 quadratic fit at 1.62 is lower than the reduced χ^2 linear fit of 2.75. The quadratic ephemeris for these recent data yields a quadratic coefficient at 3.98×10^{-12} days, nearly an order of magnitude larger than the quadratic term of the pre-2015 data, which may reflect the possible continuing presence of a third body. However, application of the Mann–Whitney U test shows no strong preference for either of these two models at the p(0.05) level.

Table 4. Eclipse minima observed between 2017 May & 2019 September

BJD	*Error (days)*	*Cycle*	*Minima*	*Filter*	*Telescope*
HS0705+6700	**T_0= 2451822.76155**				
2458050.889105	0.000036	65116	I	Clear	1
2458056.436624	0.000059	65174	I	Sloan r′	1
2458070.400908	0.000242	65320	I	Johnson V	12
2458144.336056	0.000030	66093	I	Clear	11
2458144.431452	0.000102	66094	I	Clear	11
2458144.527359	0.000041	66095	I	Clear	11
2458144.622960	0.000031	66096	I	Clear	11
2458161.552412	0.000025	66273	I	Sloan r′	11
2458162.413229	0.000046	66282	I	Sloan r′	11
2458162.509018	0.000083	66283	I	Sloan r′	11
2458212.436574	0.000126	66805	I	Johnson V	12
2458224.392311	0.000157	66930	I	Johnson V	12
2458226.496587	0.000275	66952	I	Johnson V	12
2458252.417033	0.000252	67223	I	Johnson V	12
2458258.442570	0.000203	67286	I	Johnson V	12
2458418.459648	0.000126	68959	I	Johnson V	12
2458425.441796	0.000155	69032	I	Johnson V	12
2458440.362812	0.000179	69188	I	Johnson V	12
2458440.458271	0.000206	69189	I	Johnson V	12
2458462.361467	0.000124	69418	I	Johnson V	12
2458485.412263	0.000084	69659	I	Johnson V	12
2458492.490163	0.000061	69733	I	Johnson V	12
2458512.480366	0.000236	69942	I	Johnson V	12
2458514.393247	0.000100	69962	I	Johnson V	12
2458514.488987	0.000107	69963	I	Johnson V	12
2458560.303749	0.000052	70442	I	Clear	11
2458560.494993	0.000027	70444	I	Clear	11
2458567.381801	0.000102	70516	I	Johnson V	12
2458567.477389	0.000186	70517	I	Johnson V	12
2458568.529338	0.000035	70528	I	Clear	11
2458569.390252	0.000067	70537	I	Johnson V	12
2458587.467371	0.000126	70726	I	Johnson V	12
2458593.397471	0.000098	70788	I	Sloan r′	10
2458603.440464	0.000077	70893	I	Clear	12
2458634.429954	0.000175	71217	I	Clear	12
2458708.460552	0.000166	71991	I	Clear	12
2458728.546356	0.000043	72201	I	Clear	13
2458728.546331	0.000037	72201	I	Clear	11
2458734.572115	0.000045	72264	I	Clear	13
2458740.502201	0.000102	72326	I	Clear	13
NN Ser	**T_0= 2447344.524368**				
2457899.487998	–	81142	I	Clear	1
2457908.073445	–	81208	I	Luminance	7
2458176.949347	0.000040	83275	I	Sloan g′	1
2458216.884018	0.000117	83582	I	Clear	1
2458230.152189	0.000074	83684	I	Luminance	7
2458218.834981	0.000254	83597	I	Clear	1
2458220.916317	0.000138	83613	I	Clear	1
2458310.411610	–	84301	I	Clear	10
2458311.452237	0.000135	84309	I	Clear	10
2458314.444288	0.000079	84332	I	Clear	10
2458377.663256	–	84818	I	Clear	3
2458377.663086	0.000079	84818	I	Clear	6
2458603.092126	0.000017	86551	I	Johnson V	8
2458610.116434	0.000015	86605	I	Johnson R	8
2458666.961549	0.000013	87042	I	Johnson R	8
2458716.782250	0.000016	87425	I	Johnson R	9

Continued on p.361, with explanatory notes

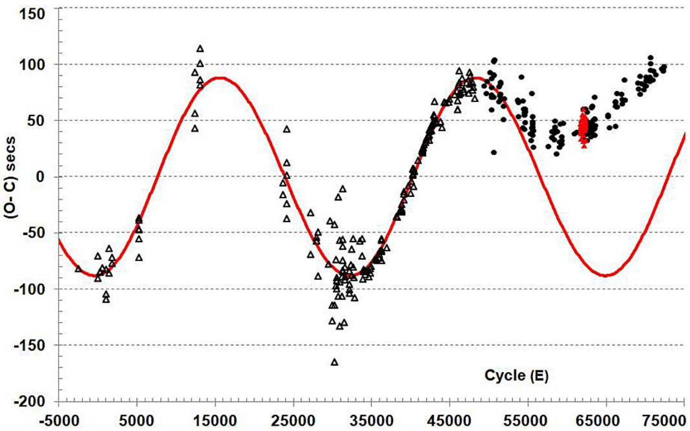

Figure 1. HS0705+6700 (O–C) residuals, with the 8.55y circumbinary brown dwarf companion represented by the red line. Open triangles are known historical data and red triangles are Bosenberger's data corrected for mid-exposure time; our new data are shown as solid black circles.

NSVS 14256825 (V1828 Aql)

Background

Since its discovery there have been many predictions for circumbinary objects orbiting NSVS 14256825. This binary system was first discovered as a magnitude 13.2 variable star during the Northern Sky Variability Survey (NSVS). Subsequently Wils *et al.* (2007) identified it as a short-period, ~2.6h eclipsing binary with an sdOB primary and a cool M dwarf or brown dwarf secondary.[22]

Observations by Qian *et al.* (2010) indicated a cyclical change in the binary period and they attributed it to a possible third body.[16] Kilkenny & Koen (2012) published nine times of minima, noting the binary period was rapidly increasing.[23] Beuermann *et al.* (2012) recorded 27 new times of minima and included a further five times extracted from the All Sky Automated Survey (ASAS) and NSVS databases using phase-folding techniques.[19] These five data points had significantly larger uncertainties, of the order of 50s, but enabled the timeline to be extended back almost eight years to 1999. They also noted that post-2009 the binary period increased significantly, suggesting the presence of a poorly-constrained circumbinary object of mass ~12M$_J$ and period of some 20y.

Almeida *et al.* (2013) performed a new circumbinary analysis while presenting 10 new times of minima.[24] They interpreted the binary period variations as the result of LTT effects introduced by two circumbinary planets with orbital periods of 3.5 & 6.9y, and masses 3 & 8M$_J$, respectively. Subsequently Hinse *et al.* (2014) suggested that a local minimum had been found and that a longer observational timeline was needed.[25] Similarly, an analysis by Wittenmeyer *et al.* (2013) showed that the proposed two planets are dynamically unstable with a projected lifetime of < 1Myr, substantially shorter than the age of this system.[26]

A third circumbinary model was put forward by Nasiroglu *et al.* (2017) who combined a further 83 new times of minima spanning 2009 August to 2016 November with existing data, but excluded data from ASAS, NSVS and SuperWASP due to their large uncertainties.[27] Their analysis suggested a possible brown dwarf circumbinary companion with a minimum mass of ~15M$_J$ and period of ~10y. Their results, and a further 19 times of minima from Pulley *et al.* (2018),[3] confirmed that the Almeida two-planet model failed to correctly predict eclipse times beyond 2013 March.

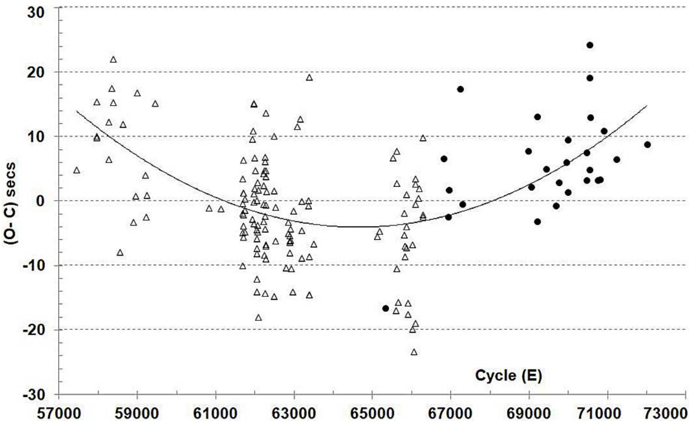

Figure 2. HS0705+6700 (O–C) residuals post- 2015 March and derived from the new linear ephemeris, Equation 3, indicating the presence of a quadratic component but with no strong indication of the earlier cyclical component of amplitude ~85s (see Figure 1). Historical data are shown with open triangles and our latest data as solid circles.

A further 84 times of minima published by Zhu *et al.* (2019) showed a deviation from the Nasiroglu circumbinary brown dwarf model.[28] With their new observations, Zhu revised the circumbinary prediction, with a brown dwarf having a minimum mass of 14.15M$_J$ and orbital period of 8.83y.

New observations

We report a further 30 times of minima observed between 2017 September and 2019 September. Excluding ASAS and NSVS data points, we compute a new ephemeris:

$$T_{\text{min, BJD}} = 2454274.20921(4) + 0.110374105(2)E + \tau \qquad [4]$$

where τ is the LTT contribution from the third body. We compute the LTT parameters, τ, from Equation 2. For the purposes of this paper, we have followed the Nasiroglu and Zhu approach and omitted the five sky survey data points, computing the parameters for a single circumbinary model. Parameters for this model are listed in Table 5 alongside earlier published models. The plot of (O–C) residuals for our new model is shown in Figure 3 where the early ASAS and NSVS datasets, together with their uncertainties, have been shown for completeness.

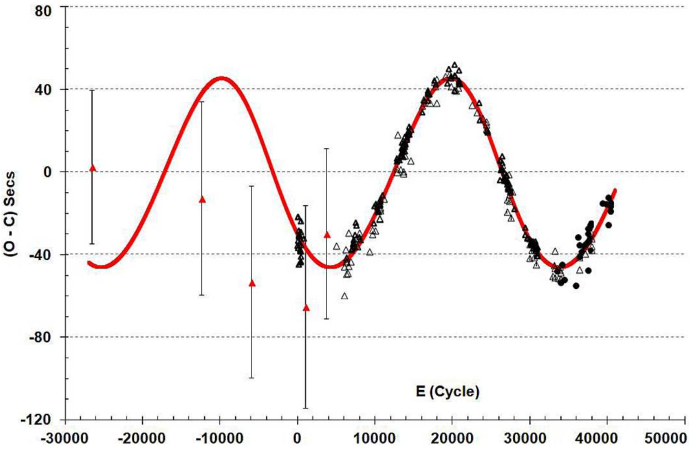

Figure 3. (O–C) residuals for NSVS 14256825 based on our revised ephemeris, Equation 4, and the single circumbinary object hypothesis. Open triangles indicate historical data; solid black circles are our new data; red triangles are Beuermann's ASAS and NSVS phase-folded data. The red curve represents the predicted (O–C) residuals based on the proposed third body.

NN Ser

Background

NN Ser is a magnitude 16.5 short-period, $\sim$3.1h binary system with a white dwarf primary and M dwarf secondary, sharing many evolution similarities with the sdB binary NSVS 14256825. It is the only WD short-period binary to show strong evidence to support the presence of circumbinary objects. NN Ser was first investigated in 1989 by Haefner, who identified it as a pre-cataclysmic binary with a deep primary eclipse (>4.0mag) with strong reflection effects from the close-by M dwarf secondary.[29] System parameters were first determined by Woods & Marsh (1991) and refined by Catalan *et al.* in 1994.[30,31] Further times of minima were obtained by Haefner *et al.* in 2004.[32]

Variability in the period of this system was first noted by Brinkworth *et al.* in 2006 when they reported 13 new times of minima, whilst extending the observational baseline to 15 years.[11] Their analysis ruled out many possible causes of the period change, *e.g.* apsidal motion, gravitational waves and magnetic Applegate effects, preferring either angular momentum loss through magnetic braking or the possibility of a low-mass circumbinary companion. However, their parameters for a putative third body were poorly constrained. Qian *et al.* (2009) added five new times of minima and suggested that the data indicated a cyclical change in the binary period, with a superimposed long-term period decrease.[33] They attributed the cyclical effect to the presence of a circumbinary planet of mass $< 14.7M_J$, assigning the underlying period decrease to magnetic braking.

Beuermann *et al.* (2010) provided new eclipse times and suggested the period variation could be attributed to two circumbinary objects, with minimum masses of 6.9 & $2.2M_J$ and periods in a 2:1 resonance of 15.5 & 7.7y, respectively.[34] Beuermann *et al.* (2013) also published a further 69 times of minima and reconfirmed their earlier two-planet model, but with marginally refined orbital parameters.[35] Marsh *et al.* (2014) provided a further 25 times of minima, confirming the presence of the two planets with orbital parameters very similar to those of Beuermann's 2013 prediction.[36]

Whilst the circumbinary planet hypothesis was the most favoured explanation for the observed period variations, Parsons *et al.* (2013) explored apsidal motion as the possible cause.[37] They observed 16 secondary eclipses of NN Ser and determined the eccentricity of the binary orbit to be less than 0.001, thus ruling out apsidal precession as a cause of the period variations. A long-term study of 67 WD short-period binaries was reported by Bours *et al.* (2016) and identified the secondary companion to NN Ser as an M dwarf of spectral type M4.[12] They added a further 10 times of minima and confirmed that their new data fitted a two-planet model, but noted that to get the best fit they had to add an additional quadratic term to the ephemeris. This new term causes the period to increase, with the most probable explanation being a distant third body. Hardy *et al.* (2016) obtained more observations from the Atacama Large Millimetre Array (ALMA), detecting thermal emissions from a dust disc of mass $\sim 0.8M_{\mathrm{Earth}}$ and postulating its origin to be from common envelope material not expelled from the system.[38] They argued that, whilst not confirming the existence of planets, this added to the possibility of the formation of so-called 'second generation' planets.

Table 4. Eclipse minima observed between 2017 May & 2019 September (cont'd from p.359)

BJD	*Error (days)*	*Cycle*	*Minima*	*Filter*	*Telescope*
NSVS 01286630 T_0= 2454272.753960					
2458306.490912	0.000130	10506.5	II	Johnson V	12
2458315.514056	0.000110	10530	I	Johnson V	12
2458317.433500	0.000212	10535	I	Johnson V	12
2458322.424583	0.000150	10548	I	Johnson V	12
2458325.496040	0.000138	10556	I	Johnson V	12
2458332.406650	0.000150	10574	I	Johnson V	12
2458335.477738	0.000089	10582	I	Johnson V	12
2458345.459948	0.000124	10608	I	Johnson V	12
2458379.437658	0.000143	10696.5	II	Johnson V	12
2458380.397297	0.000049	10699	I	Clear	11
2458390.379420	0.000067	10725	I	V	11
2458450.656220	0.000070	10882	I	Sloan g′	1
2458533.584079	0.000098	11098	I	V	11
2458540.494919	0.000060	11116	I	R	11
2458547.405424	0.000207	11134	I	Sloan r′	11
2458555.468052	0.000135	11154	I	Sloan r′	11
2458560.459039	0.000184	11168	I	Johnson V	12
2458608.450030	0.000065	11293	I	Clear	12
2458626.494596	0.000063	11340	I	Clear	12
2458679.476185	0.000180	11478	I	Clear	12
2458687.538711	0.000088	11499	I	Clear	12
2458728.618856	0.000071	11606	I	IRB	13
NSVS 14256825 T_0= 2454274.209211					
2458017.436008	0.000043	20146	I	Clear	4
2458039.290180	0.000049	20344	I	Sloan r′	10
2458073.285319	0.000034	20652	I	Luminance	4
2458229.243900	0.000044	22065	I	Johnson V	2
2458264.343135	–	22383	I	Johnson V	2
2458288.183832	0.000063	22599	I	Johnson V	2
2458288.294274	0.000139	22600	I	Johnson V	2
2458311.252050	0.000035	22808	I	Johnson V	2
2458341.163464	0.000074	23079	I	Johnson V	2
2458370.081490	0.000013	23341	I	Clear	2
2458395.357172	0.000057	23570	I	Johnson V	12
2458407.332810	0.000379	23678.5	II	Johnson V	12
2458411.361260	0.000163	23715	I	Johnson V	12
2458412.354860	0.000074	23724	I	Johnson V	12
2458440.610650	0.000240	23980	I	V	5
2458418.646110	0.000050	37549	I	Sloan r′	1
2458424.606320	0.000030	37603	I	Sloan r′	1
2458429.573220	0.000020	37648	I	Sloan r′	1
2458435.643740	0.000030	37703	I	Sloan r′	1
2458442.597240	0.000060	37766	I	Sloan r′	1
2458451.648070	0.000030	37848	I	Sloan r′	1
2458453.634790	0.000030	37866	I	Sloan r′	1
2458610.255774	0.000056	39285	I	V	2
2458662.131600	0.000020	39755	I	V	2
2458692.043017	0.000223	40026	I	V	2
2458692.153239	0.000067	40027	I	V	2
2458721.402501	0.000022	40292	I	Clear	12
2458722.395865	0.000056	40301	I	IRB	13
2458726.369288	0.000026	40337	I	IRB	13
2458728.466423	0.000016	40356	I	IRB	13

The reference epoch is noted for each binary system in each section header. See Table 3 for telescope reference.

New observations & ephemeris

We report 16 new times of minima for NN Ser, observed between 2017 May and 2019 August. The light curve for NN Ser's primary eclipse (Figure 4) shows the compact nature of the WD primary, which gives rise to a deep primary minimum with steep ingress and egress. Our times of minima were calculated by fitting straight lines to the ingress and the egress portions of the light curve and determining the mid-point between these two lines. Uncertainties of less than 3s were achieved with 2-metre aperture telescopes.

Table 5. Comparison of the circumbinary models for NSVS 14256825

	Beuermann 2012	*Almeida* 2013		*Nasiroglu* 2017	*Zhu* 2019	*This paper*
BINARY PARAMETER						
Binary epoch (+240000), BJD	54274.208923(4)	54274.20874(4)		55793.84005(3)	54274.20921(1)	54274.20921(4)
Binary period, days	0.1103741324(3)	0.1103741681(5)		0.110374099(3)	0.1103741030(5)	0.110374105(2)
THIRD BODY		*Body 1*	*Body 2*			
Star survey data included		Yes	Yes	No	No	No
LTT amplitude, secs	59	85(3)	5.0(3)	48.10(1)	46.3(4)	46.0(5)
Eccentricity	0.5	0.52(8)	0.00(+8)	0.175(12)	0.12(2)	0.11(10)
Period, years	20	6.86(45)	3.49(38)	10.96(41)	8.83(6)	8.94(51)
Periastron passage, BJD	2454836	2456643(110)	2455515(95)	7938.5(204)	2456816(94)	2456825(48)
Longitude of periastron, rads	4.57	1.71(15)	0.19(14)	1.57(24)	2.33(18)	2.37(10)
Mass (i= 90°), M_J	12	8.0(15)	2.10(4)	14.75(13)	14.15(0.16)	14.53

Recent data from Zhu *et al.* (2019) and this paper show a departure from the Nasiroglu *et al.* (2017) model, reflected in the smaller orbital eccentricity and shorter third body period.

Notes: Parameters for Beuermann *et al.* (2012) are poorly constrained. Uncertainties specified for Nasiroglu *et al.* (2017) are asymmetric; those above are mean values. Almeida used two of the five ASAS/NSVS data points (cycle 1018 and 3737).

For smaller apertures uncertainties were substantially higher; see Table 4.

With our new data, together with all known published data, and using the Beuermann *et al.* (2013) ephemeris:[35]

$$T_{\text{min, BJD}} = 2447344.524368(7) + 0.13008014203(3)E + \tau \qquad [5]$$

where τ is the circumbinary LTT parameter. The resulting (O–C) residuals are shown in Figure 5. We first noted a departure from the two-circumbinary-planet model in mid-2017 ($E \sim 80{,}000$). With our recent data we can confirm that the original two-planet circumbinary model predicted by Beuermann, Marsh and Bours needs to be reviewed as more data are collected.

NSVS 01286630

Background

NSVS 01286630 (NSVS 1135262 in SIMBAD) is a detached eclipsing binary with a short orbital period of 9.2h, deep symmetric primary and secondary eclipses, that was first identified as a low-mass binary (LMB) by Shaw & Lopez-Morales in 2007.[39]

Coughlin & Shaw (2007) observed light curves and derived stellar parameters for this system, determining its principal properties as M_1 = 0.68M$_\odot$, R_1= 0.081R$_\odot$, T_1= 4,140K and M_2= 0.72M$_\odot$, R_2= 0.87R$_\odot$, T_2= 4,290K.[40] They noted that LMBs had a high level of starspot activity and, to achieve the best light curve fit, they modelled the system with two starspots on the hotter secondary component.

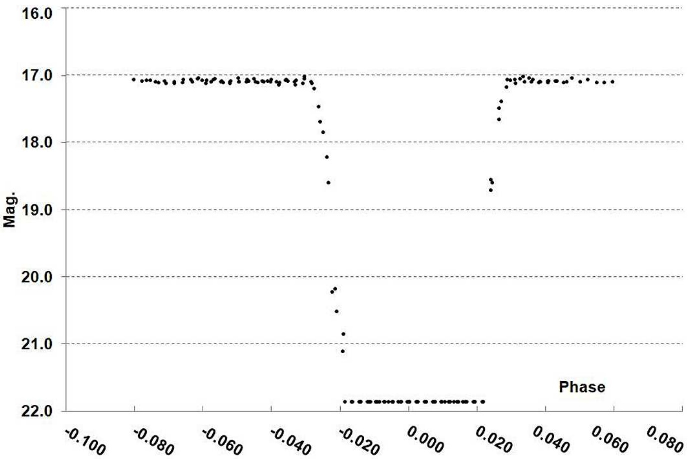

Figure 4. The light curve of NN Ser's primary minimum, showing the steep ingress and egress as would be expected from the eclipse of a compact white dwarf primary star. The out-of-eclipse rising and falling shoulders, from the secondary reflected light, are also present in the full NN Ser light curve.

Wolf *et al.* (2016) added 94 times of minima, observed between 2005 November and 2016 May, and identified a cyclical variation in the binary period which they attributed to an LTT effect.[41] From this they deduced the presence of a 0.103-stellar-mass third body, orbiting with a period of 3.62y. Zhang *et al.* (2018) observed five times of minima between 2010 November and 2011 June, deriving a similar ephemeris and third-body parameters to those proposed by Wolf.[42] Both Wolf and Zhang considered the possibility of a magnetic Applegate-type mechanism driving the LTT effect, but discarded this in favour of a circumbinary object.

New observations & ephemeris

To investigate whether the circumbinary model of Wolf and Zhang continues to hold beyond 2015 November, we present 22 new times of primary minima observed between 2018 July and 2019 September. We have adopted the ephemeris of Zhang *et al.* (2018), first converting time from Heliocentric Julian Date to BJD:

$$T_{\text{min, BJD}} = 2454272.753960 + 0.3839278700E + \tau \qquad [6]$$

where τ is the contribution from the putative circumbinary third body given by Equation 2. The third body is suggested to orbit the binary pair at a distance of 3.7au, with a period of 3.6 years and orbital eccentricity of 0.08. Application of this ephemeris with our new data is shown in Figure 6, strongly suggesting that the circumbinary models of both Wolf and Zhang may need modifying over the extended timeline. More data over the coming months is required to clarify this potential anomaly.

Discussion

Historically, the approach adopted to determine the presence of circumbinary objects around sdB eclipsing binaries has been to first identify a cyclical behaviour within the eclipse timing measurements, and then to note all possible causes. The improbable causes are then eliminated and whatever remains is assumed to

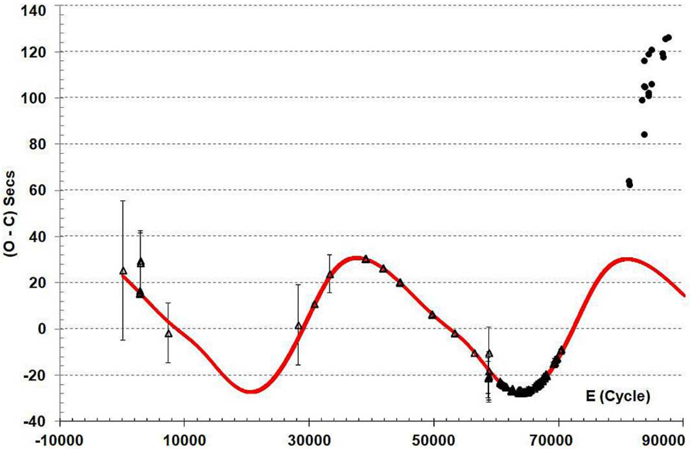

Figure 5. NN Ser (O–C) residuals with linear ephemeris removed. Historical data are shown with open triangles and solid points are our new data. The red line is the two-planet hypothesis of Beuermann *et al*. (2013). Observations depart from predictions at $E \sim 80{,}000$, corresponding to mid-2017.

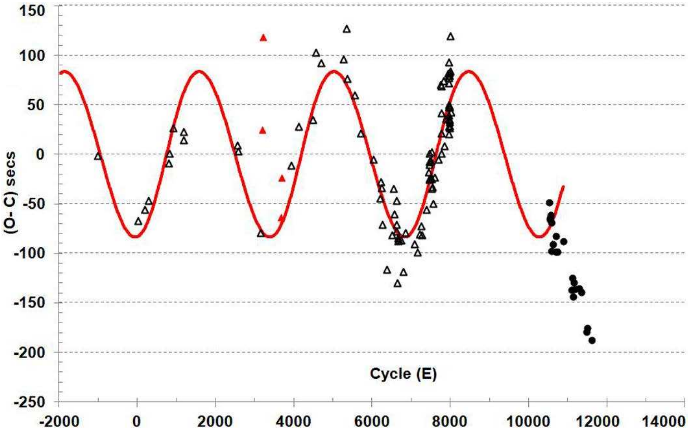

Figure 6. The plot of (O–C) residuals for NSVS 01286630, adopting the ephemeris and circumbinary properties from Zhang *et al*. (2018). Our new data are shown as solid black circles; all historical data are shown as open triangles with the Zhang data as red triangles. Zhang's fifth point (at 3804, −334.99) is out of range of this chart.

provide the most likely explanation of the observed behaviour. In the case of sdB PCEB systems, the remaining cause has invariably been attributed to a circumbinary companion. Whilst this reasoning is sound, it does contain a number of underlying assumptions including (i) having a knowledge of all possible causes of cyclical ETVs; (ii) having a complete understanding of the mechanisms behind these causes and (iii) the cyclical behaviour being stable over at least several periods of each circumbinary object.

The complexity of these systems may undermine some of these assumptions. Whilst the systems are described simplistically as detached, *i.e.* there is no mass transfer between them, modelling has shown that the reality may be far more complicated. The 'surfaces' of the binary pair are typically separated by less than a solar radius, and with the effective temperature of the secondary companion being of the order of 3,000K, it is heavily irradiated by the primary which is significantly hotter at *circa* 30,000K. Whilst there is no mass transfer, the energy interaction is likely to be complex and a modified Applegate-type mechanism may be significant. It is frequently noted from light curve solutions of these systems that an improved fit can be found when the bolometric albedo of the secondary is set to a nonphysical value of greater than unity; see for example Drechsel *et al*. (2001).[13]

There too remains the open question of how circumbinary planets form around these systems and whether they are first- or second-generation objects – *i.e.*, whether they were formed before or after the common envelope ejection, or possibly a combination of both; see for example Schleicher & Dreizler (2014).[43]

We note that in three of the four systems we have investigated (HS 0705+6700, NN Ser and NSVS 01286630) there is a significant visual departure from the historic (O–C), possibly indicating a change within the binary system. These departures suggest a small increment of a few tens of milliseconds in the PCEB period, and could mask the presence of circumbinary objects. This is particularly so for HS 0705+6700, for which we have gathered four years of data since the observed change, reflecting a binary period increase of some 11ms. Whilst seemingly small it is significant in comparison with the 8,300s period of the binary system. If a similar magnitude of change were to occur between the Earth and Sun, we would see the Earth year increase by 40s over a period of a few months.

If there was a circumbinary object present prior to this binary period increase – and there are 1.7 cycles of data to suggest this – the question remains as to whether this object is still present. Our analysis of the last four years of data suggests that, so far, there is no strong indication for the presence of a cyclical signal attributable to a circumbinary object.

NN Ser shows a similar trend to HS 0705+6700, with a small period increase noted from mid-2017. Unlike its sdB counterpart, this system does not, as yet, give any strong indication of a cyclical or quadratic component within the new data. However, with an out-of-eclipse magnitude of 16.5, NN Ser does require the use of large optics to acquire high-precision data.

NSVS 01286630, an LMB-type object which has not progressed to the PCE stage, has been included to provide a contrast with the other three short-period PCEB systems reported here. Whilst this object has shown a binary period decrease of 110ms, there is again no clear indication of a circumbinary or quadratic component in the new data. However, with little more than one year of new data, a longer timeline is necessary.

In contrast to the above three systems, the sdB NSVS 14256825 does show a cyclical 8.9-year period, with data spanning the past 12 years. However, as new data have been acquired, each previously proposed circumbinary model has failed. The validity of our new model will only be confirmed when observations over the coming five or six years provide two full cycles of consistent data. We note that all recent analyses of this system have ignored the early phase-folded light curve data of Beuermann *et al.*[19]

Conclusions

Whilst it is well known that observations of eclipse time variations can be used to detect circumbinary objects, the considerations outlined in the Discussion can make it difficult to interpret ETVs, particularly if timelines are short (as they frequently are) in comparison with the longest circumbinary period. For acceptable confidence levels, minimum observational timelines of twice the longest circumbinary period are suggested. These difficulties are reflected in the NASA Exoplanet Archive, where there are only 16 exoplanets listed using the ETV methodology out of a total of some 4,296 confirmed exoplanets. There are also instances where claims have been refuted and planets removed, *e.g.* HW Vir.

Although our new data and analysis conflict with earlier interpretations, and in most cases do not necessarily confirm the presence of stable circumbinary objects around these systems, they may also indicate that post-common envelope binaries are going through complex transitory phases. Our new data have shown departure from early predictions for three of the four systems, but it is premature to conclude that these results rule out the presence of circumbinary objects.

Of the systems we have investigated in this and our previous papers, only three have confirmed circumbinary planets included in the NASA Exoplanet Archive: NY Vir b, NSVS 14256825 b and NN Ser c & d. It is noted that the longer, ~25 year period companion to NY Vir, computed by both Lee and Song, has not been included in the NASA database, and NSVS 14256825 has only 1.3 cycles of confirmed data so far. Similarly, only one of some 40 WD PCEBs, NN Ser, has identified circumbinary planets. Whilst NN Ser's two circumbinary planets have been listed on the NASA database, our new results now raise questions on their presence/parameters.

Finally, we reiterate that additional observations over a longer timeline are required to increase confidence in the many circumbinary claims for post-common envelope binary systems that have been made over the past decade. Indeed, this increased timeline may show further complex changes in these ETVs.

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Editorial postscript

George Faillace (*d.* 2020 Mar 19) will be remembered as an outstanding observer and friend to many in the BAA. An obituary written by David Pulley, co-author on this paper, is on p.372. – *Ed.*

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Appendix: Evolutionary scenarios for post-common envelope binary systems

Various evolutionary scenarios have been proposed for PCEB systems, but a definitive mechanism remains to be found. Favoured models suggest that when the more massive primary evolves to the red giant phase it fills its Roche lobe and matter is transferred from the primary star to its smaller main-sequence companion, at a rate that cannot be accommodated by the smaller star. This unstable mass transfer from the primary forms a common envelope that surrounds the helium-burning core of the red giant primary and its companion. As a consequence angular momentum is transferred from the binary system to the surrounding envelope, bringing the binary pair closer together and resulting in a short binary period of typically between two and three hours. Eventually the common envelope acquires sufficient angular momentum for it to be mostly ejected from the system, so creating a planetary nebula surrounding a detached binary system.

As the common envelope phase is of short duration, the mass of the smaller companion remains substantially constant since it was unable to accommodate the mass transfer. The remaining mass of what is left of the red giant, the primary, is about equal to the mass of the core of the giant at the onset of mass transfer. The helium-rich primary forms an sdB star, as in the case of HS 0705+6700 and NSVS 14256825, and is well on its way to becoming a white dwarf, for example NN Ser. Eventually, the loss in angular momentum will bring the binary pair into close proximity, producing a classic cataclysmic variable.

NSVS 01286630 is somewhat different, being a system that has not yet filled its Roche lobes, but in time the more massive star will become a red giant and follow a similar path to other sdBs as described above.

How planets are formed around PCEB systems remains an unanswered question and two scenarios are postulated. The first-generation hypothesis suggests planets are formed before the expulsion of the common envelope, so surviving this cataclysmic event; see for example Hardy *et al.* (2016) and Parsons *et al.* (2014) using primarily the NN Ser system as a model.[38,44] The second-generation hypothesis suggests planet formation occurs after the expulsion of the common envelope and from the remaining protoplanetary disc. This hypothesis is strongly supported from simulations by Zorotovic & Schreiber (2013) and Schleicher & Dreizler (2014).[1,43]

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