A&A 540, A8 (2012)
DOI: 10.1051/0004-6361/201118105

Astronomy & Astrophysics

The quest for companions to post-common envelope binaries

II. NSVS14256825 and HS0705+6700

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Received 15 September 2011 / Accepted 16 January 2012

ABSTRACT

We report new mid-eclipse times of the two close binaries NSVS14256825 and HS0705+6700, harboring an sdB primary and a low-mass main-sequence secondary. Both objects display clear variations in their measured orbital period, which can be explained by the action of a third object orbiting the binary. If this interpretation is correct, the third object in NSVS14256825 is a giant planet with a mass of roughly 12 $M_{\rm Jup}$. For HS0705+6700, we provide evidence that strengthens the case for the suggested periodic nature of the eclipse time variation and reduces the uncertainties in the parameters of the brown dwarf implied by that model. The derived period is 8.4 yr and the mass is 31 $M_{\rm Jup}$, if the orbit is coplanar with the binary. This research is part of the *PlanetFinders* project, an ongoing collaboration between professional astronomers and student groups at high schools.

Key words. binaries: close – binaries: eclipsing – subdwarfs – stars: individual: NSVS14256825 – stars: individual: HS0705+6700 – planets and satellites: detection

1. Introduction

Some eclipsing close binaries exhibit O–C variations in the observed mid-eclipse times relative to those calculated from an underlying linear ephemeris. An early example is the cataclysmic variable UX UMa, which displayed what looked like a periodic variation with an amplitude of 150 s and a period of 29 yr. This modulation was interpreted as being possibly caused by a third body (Nather & Robinson 1974) or by apsidal motion (Africano & Wilson 1976) until Rubenstein et al. (1991) proved its aperiodic nature. Since then an explanation of these variations by processes internal to the binary has been favored, which need not be periodic. One such process (Applegate 1992) involves changes in the internal constitution of the secondary, which give rise to changes in its spin and variations in the orbital period by spin-orbit coupling. With more data becoming available, it was realized, however, that internal processes might be too feeble to explain the observations (e.g. Brinkworth et al. 2006; Chen 2009; Schwarz et al. 2009; Potter et al. 2011), but this notion was opposed by Wittenmyer et al. (2012). It was also realized that the detached post-common envelope binaries (PCEBs) represent more suitable laboratories for studying eclipse time variations than the accreting cataclysmic variables, in particular, the variety to which UX UMa belongs. With this in mind, the interpretation of eclipse time variations in terms of the light-travel time effect produced by a third body was revived in a series of papers by Qian et al. (2009, 2010a,b, and references therein). An intriguing case is the semi-detached cataclysmic variable HU Aqr, which displays multi-periodic O–C variations. Qian et al. (2011) attributed these variations to the effects of two planets orbiting the binary, but Horner et al. (2011) and Wittenmyer et al. (2012) demonstrated the secular instability of the proposed planetary system and questioned its existence. While this case remains unresolved, the evidence of systematic and possibly periodic eclipse time variations in detached PCEBs increases.

The 14.7 mag star HS 0705+6700 (in short HS0705) was discovered by Drechsel et al. (2001) to be an eclipsing close binary with an orbital period of 2.3 h, consisting of an sdB primary and an M-dwarf secondary. Qian et al. (2009, 2010a) summarized all the then available eclipse times and, fitting a sinusoidal to the data, suggested the presence of a brown dwarf orbiting the binary with a period of 7.15 yr.

NSVS 14256825 (in short NSVS1425) was discovered as a 13.2 mag variable star in the Northern Sky Variability Survey (Woźniak et al. 2004) and identified as an eclipsing binary with a 2.6 h orbital period and an sdB primary by Wils et al. (2007). The source seems to be in many respects a twin of HS0705 and the prototype sdB/M-dwarf binary HW Vir (Lee et al. 2009).

2. Observations and data analysis

We present here the results of an ongoing search for eclipse time variations in these two sources, which is based on new

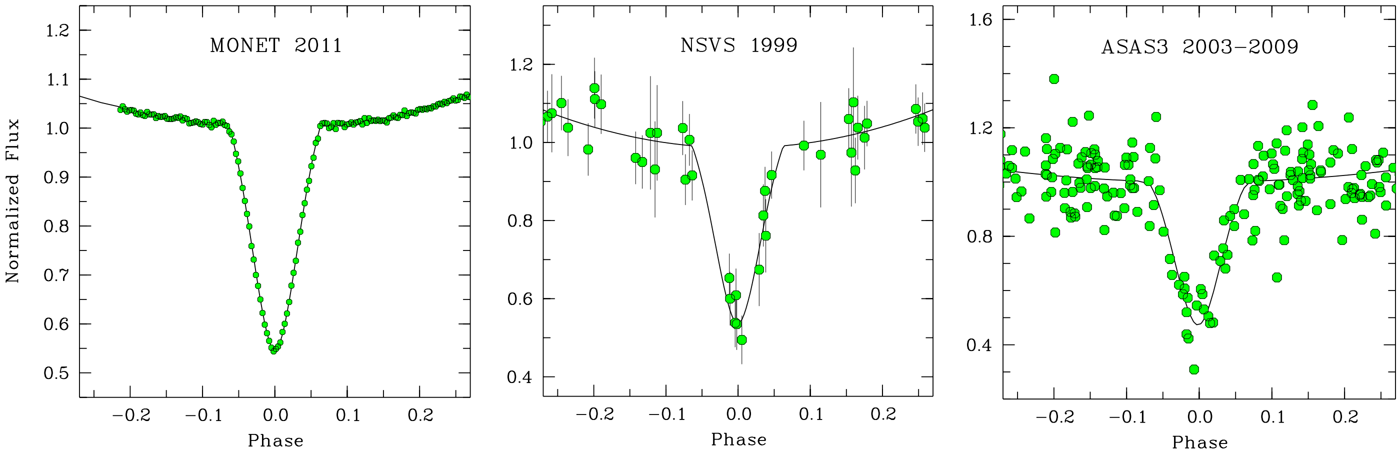

Fig. 1. Eclipse light curves of NSVS 14256825. *Left:* MONET/N on 5 May 2011, *center:* Northern Sky Variability Survey, April–August 1999, *right:* All Sky Automated Survey 3.

observations extending throughout 2011 and supplemented by archival data reaching back to 1999. Part of the 2011 observations were performed within the project *PlanetFinders* conducted by high-school teachers and their students in collaboration with professional astronomers. This project provides high school students with first-hand experience in all aspects of an authentic research project.

NSVS1425 and HS0705 were observed with the MONET/North telescope at the University of Texas' McDonald Observatory via the MONET browser-based remote-observing interface between April and December 2011. The photometric data were taken with an Apogee ALTA E47+ 1k × 1k CCD camera in white light, with exposure times of usually 20 s. Using MONET/North, high school students carried out part of the observations from their classroom. Additional observations with integration times between 20 s and 100 s were performed with the 1.0-m Vihorlat National Telescope at Kolonica Saddle, Slovakia, equipped with an FLI PL1001E CCD in white light; with the 84-cm reflector of the Observatorio Astronomico Nacional en San Pedro Martir, Mexico, in Johnson V; and with the 65-cm reflector at Ondřejov Observatory, Czech Republic, with a G2-3200 CCD Camera and R_c filter. All data were subjected to the usual dark current subtraction and flatfielding. Relative photometry was performed using suitable comparison stars. Figure 1 (left panel) shows a light curve of NSVS1425 taken with the MONET/N telescope on 5 May 2011 along with the model fit described below.

Early coverage of HS0705 and NSVS1425 is available from archival data of the Northern Sky Variability Survey (Woźniak et al. 2004)[1], which provides short glimpses of the sky for an extended period of time in 1999, with exposure times between 20 and 80 s. HS0705 was extensively studied from October 2000 on by Drechsel et al. (2001). The source was subsequently monitored by Qian et al. (2009, 2010a, and references therein). For NSVS1425, on the other hand, there is a dearth of data between 1999 and 2007, when Wils et al. (2007) noted its eclipsing nature. Fortunately, the source was covered by the All Sky Automated Survey 3 performed from Chile (Pojmański 2004)[2] with eclipses contained in data from 2003 to 2009. Again, the survey provides only glimpses of the source with its short series of usually 180 s exposures in the V-band. By folding the barycentrically and leap-second corrected data over the known period, mean eclipse light curves can be reconstructed from both the NSVS and the ASAS3 data. These are displayed in the center and right panel of Fig. 1. The model light curves employ parameters fixed at the values determined from fits to the MONET/N data (see next paragraph). The NSVS data that contain eclipses of NSVS1425 cover the period from 19 April to 10 August 1999. The ASAS3 data can be broken up into four light curves defining representative mid-eclipse times for dates in 2003, 2005, 2007, and 2008.

We fitted the eclipse light curves obtained with the MONET/N, Kolonica, Ondřejov, and San Pedro Martir telescopes, using a heuristic model that involves no physics, except requiring symmetry about the mid-eclipse time p_1. In the variable $\tau = t - p_1$, with t the time, the observed relative flux $F(t)$ is represented by a modified and truncated inverted Gaussian $G(\tau)$ multiplied by a polynomial $P(\tau)$ that accounts for any real or apparent variation in the out-of-eclipse flux, i.e.,

$$F(t) = P(\tau)\min\left(1, G(\tau)\right), \quad (1)$$

where

$$G(\tau) = p_2 - p_3 \exp\left[-\frac{1}{2}\left(\frac{|\tau|}{p_4}\right)^{p_5}\right], \quad (2)$$

$$P(\tau) = p_6 + p_7\,\tau + p_8\,\tau^2, \quad (3)$$

and $p_i, i = 1\ldots8$, are the fit parameters. The Gaussian is modified by replacing the square in the exponential with a free parameter p_5, which allows the creation of a more peaked or broader shape of the eclipse light curve. With a zero level p_2 exceeding unity, the truncation provided by the prescription of Eq. (1) reproduces the finite base width of the eclipse. At each step of the iterative fitting procedure, $F(t)$ is furthermore averaged over the finite, not necessarily equidistant exposure intervals.

Figure 1 shows that a close to perfect fit to the observed light curve is achieved. For exposure bins of 20 s, the achievable accuracy of the derived mid-eclipse times is ∼1 s for the primary eclipses and a few seconds for the secondary eclipses. The formal errors in the mid-eclipse times derived from fits to the NSVS and ASAS3 data amount to about 1 min.

3. Results

3.1. NSVS14256825

Table 1 lists the new mid-eclipse times for NSVS1425, along with the formal errors from the light curve fits. These data

[1] http://skydot.lanl.gov/
[2] http://www.astrouw.edu.pl/~asas3/

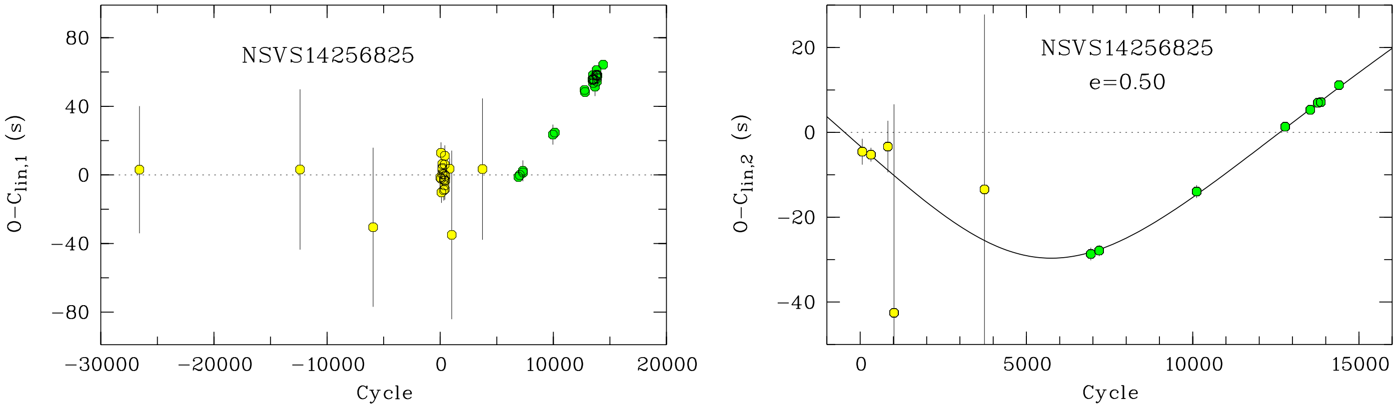

Fig. 2. O–C diagrams for NSVS14256825 with previously published and our new data shown as yellow and green dots, respectively. *Left*: residuals O–C$_{lin,1}$ for a linear ephemeris fitted to the pre-2010 data, cycle numbers $E < 9000$ (dotted line). *Right*: residuals O–C$_{lin,2}$ for an elliptic orbit fit relative to the underlying linear ephemeris of the binary (Eq. (4)). Weighted mean data points for cyles $E \geq 0$ are displayed (see text).

Table 1. New mid-eclipse times of NSVS14256825 and O–C$_{ell}$ residuals of the elliptic orbit fit displayed in Fig. 2, right panel.

Cycle E	Ecl	BJD(TT) (days)	Error (days)	O–C$_{ell}$ (days)	Tel[†]
−26586.0	I	51 339.803273	0.000429	0.000016	1
−12390.0	I	52 906.673899	0.000541	−0.000271	2
−5931.0	I	53 619.579776	0.000537	−0.000573	2
1018.0	I	54 386.569297	0.000569	−0.000375	2
3737.0	I	54 686.676900	0.000477	0.000140	2
6914.0	I	55 037.335341	0.000018	−0.000006	3
7037.0	I	55 050.911367	0.000022	−0.000002	4
7304.0	I	55 080.381278	0.000071	0.000008	3
7322.0	I	55 082.368000	0.000021	−0.000005	3
9823.5	II	55 358.468971	0.000046	−0.000053	5
9959.0	I	55 373.424740	0.000068	0.000012	5
10131.0	I	55 392.409097	0.000018	0.000008	5
12763.0	I	55 682.913998	0.000013	0.000013	6
12799.0	I	55 686.887451	0.000013	−0.000005	6
12799.5	II	55 686.942699	0.000031	0.000056	6
13469.0	I	55 760.838180	0.000027	0.000008	6
13469.5	II	55 760.893396	0.000031	0.000037	6
13470.0	I	55 760.948549	0.000011	0.000003	6
13488.0	I	55 762.935315	0.000018	0.000034	6
13542.0	I	55 768.895489	0.000037	0.000001	6
13632.0	I	55 778.829154	0.000010	−0.000012	6
13511.0	I	55 765.473867	0.000017	−0.000021	3
13682.0	I	55 784.347812	0.000064	−0.000064	5
13768.0	I	55 793.840061	0.000012	0.000004	6
13827.0	I	55 800.352168	0.000014	0.000032	3
13828.0	I	55 800.462510	0.000013	0.000000	3
13845.0	I	55 802.338869	0.000024	−0.000002	3
13846.0	I	55 802.449197	0.000036	−0.000048	3
13872.0	I	55 805.318959	0.000015	−0.000015	3
13873.0	I	55 805.429322	0.000017	−0.000026	3
13899.0	I	55 808.299065	0.000016	−0.000013	3
14400.0	I	55 863.596559	0.000010	0.000006	6

Notes. [(†)] (1) NSVS, (2) ASAS3, (3) Kolonica Observatory, (4) San Pedro Matir Observatory, (5) Ondřejov Observatory, (6) MONET/North.

complement the only previously published ones from Wils et al. (2007). The first five entries are from the NSVS for 1999 and the ASAS3 for time intervals of a few months in the summers of 2003, 2005, 2007, and 2008. These eclipse times are obtained from fits of the known eclipse profile to the barycentrically corrected data folded over the orbital period. The quoted Julian day is that of the lowest data point during the eclipse, but the fraction of the day is derived from the fit. Of the remaining 27 entries, 24 represent primary eclipses (I) and three secondary eclipses (II). All times were corrected to the solar system barycenter with leap seconds added and quoted as BJD(TT). We derived an ephemeris by adding the mid-eclipse times of Wils et al. (2007) converted from HJD to BJD(TT)[3].

Using either the data of Wils et al. (2007) alone or all primary mid-eclipse times until September 2009 (cycle number 7322), we obtained the same orbital periods within the errors, $P = 0.110374086(88)$ days and $P = 0.110374093(3)$ days, respectively. There is no evidence of a period change in the pre-2010 data. Figure 2 (left panel) shows the O–C$_{lin,1}$ values relative to a linear ephemeris with the latter period. The situation changes drastically for the post-2009 data, where a sharp upturn is observed, which corresponds to a rather abrupt period increase by 9 ms. A physical mechanism that can cause such a change in a detached binary is its response to a companion in a highly elliptic orbit hurdling through periastron. Similar variations in QS Vir (Parsons et al. 2010) and DP Leo (Beuermann et al. 2011) have been ascribed to the action of third bodies. While such an interpretation may seem premature for NSVS1425, it fits the available data exceedingly well and provides a definite prediction, which can be tested in the next couple of years.

Given the uncertain orbital period of the putative third body, the eccentricity is likewise uncertain, a situation that is similarly met for some comets in the solar system observed only near perihelion. Fixing the period at $P_3 = 20$ yr, similar to values found for other PCEBs, we fitted all data with the light-travel time effect produced by a third body in an elliptic orbit. The fit involves seven free parameters, five for the elliptic orbit and two for the underlying linear ephemeris of the binary (Beuermann et al. 2010, 2011). The latter is

$$\mathrm{BJD(TT)} = 54\,274.208923(4) + 0.1103741324(3)\,E, \qquad (4)$$

where E is the cycle number. The best-fit eccentricity of the 20-year orbit is $e_3 = 0.50$, but a valley of low χ^2 in the P_3, e_3 plane stretches from 14 yr, 0.30 to beyond 30 yr, 0.70. While we fitted all individual mid-eclipse times, a clearer graphical presentation is obtained by plotting the weighted mean O–C$_{lin,2}$ values relative to the ephemeris of Eq. (4) for subgroups of data taken close together in time (Fig. 2, right panel). The subgroups

[3] http://astroutils.astronomy.ohio-state.edu/time/

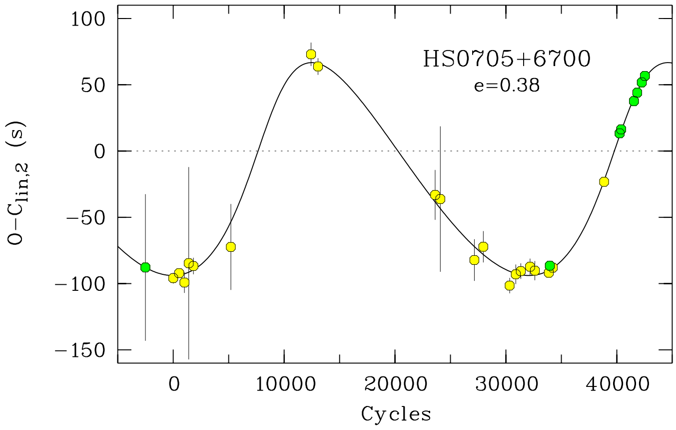

Fig. 3. Elliptic orbit fit for HS 0705+6700. Shown are the residuals O–$C_{lin,2}$ relative to the underlying linear ephemeris of the binary (Eq. (5)). Color coding is as in Fig. 2.

combine data taken over intervals of a week to about a month, which is much shorter than the suggested orbital period. The residuals of the individual new timings from the elliptic orbit fit are quoted in Table 1. The amplitude of the O–$C_{lin,2}$ variation, $K_3 \simeq 59$ s, suggests a mass of the third body of $M_3 \simeq 12\,M_{Jup}$, if we adopt a total mass of the binary of 0.62 $M_\odot$, which is similar to those of HS0705 (0.617 $M_\odot$, Drechsel et al. 2001) and HW Vir (0.627 $M_\odot$, Lee et al. 2009). The value of M_3 varies with the uncertain orbital period P_3 as $P_3^{-2/3}$ and increases with the unknown inclination i_3 of the third body as $1/\sin i_3$. If the orbit of the companion is roughly co-planar with the binary, it qualifies as a giant planet. For the 20-year orbit, the semi-major axis is 6.3 AU. Our fit yields an argument of periastron for the motion of the center of gravity of the binary measured from the ascending node in the plane of the sky $\varpi_{bin} = \varpi_3 - 180° \simeq -98°$. Periastron passage occurred near JD 2 454 836 ($E \simeq 5091$). The fit suggests that O–$C_{lin,2}$ will reach a maximum of 88 s in 2019 ($E \simeq 40\,000$), with actual numbers depending on the uncertain value of P_3.

3.2. HS0705+6700

A large body of mid-eclipse times of HS0705 has been collected by Qian et al. (2009, 2010a) and interpreted in terms of a third body with a mass of about 30 M_{Jup}, orbiting the binary with a period of 7.15 yr. Çamurdan et al. (2012) added a few timings and found a similar period. We obtained 18 more primary and three secondary eclipses of HS0705, significantly extending the coverage. In addition, we recovered an early eclipse timing from the NSVS. The new data are listed in Table 2.

We fitted the entire set of 89 primary mid-eclipse times assuming that the variations are caused by a third body in an elliptic orbit. The fit yields $\chi^2 = 80.6$ for 82 degrees of freedom and is shown in Fig. 3. For a clearer presentation, we collected the individual data points again into appropriate subgroups comprising time intervals of up to a week for the more accurate data and one month for the less accurate ones near minimum O–$C_{lin,2}$ (compare Fig. 3 of Qian et al. 2010a, where the individual O–C values are displayed). The underlying intrinsic ephemeris of the binary is

$$\mathrm{BJD(TT)} = 51\,822.761677(6) + 0.0956466253(2)\,E. \quad (5)$$

The amplitude of the light-time effect produced by the third body is $K_3 = 86 \pm 1$ s, its orbital period is $P_3 = 8.41 \pm 0.05$ yr, and

Table 2. New mid-eclipse times of HS 0705+6700 and O–C_{ell} residuals of the elliptic orbit fit displayed in Fig. 3.

Cycle E	Ecl	BJD(TT) (days)	Error (days)	O–C_{ell} (days)	Tel[†]
−2509.0	I	51 582.783271	0.000640	0.000001	1
33946.0	I	55 069.581023	0.000062	0.000044	2
33977.0	I	55 072.546051	0.000062	0.000025	2
40230.0	I	55 670.625551	0.000028	0.000014	3
40251.0	I	55 672.634181	0.000025	0.000059	3
40272.0	I	55 674.642702	0.000025	−0.000004	3
40272.5	II	55 674.690594	0.000044	0.000065	3
40273.0	I	55 674.738359	0.000028	0.000006	3
40355.5	II	55 682.629077	0.000123	−0.000146	3
40356.0	I	55 682.677091	0.000025	0.000045	3
40429.0	I	55 689.659259	0.000025	−0.000011	3
41488.0	I	55 790.949290	0.000025	−0.000022	3
41519.0	I	55 793.914357	0.000025	−0.000008	3
41529.5	II	55 794.918598	0.000044	−0.000058	3
41540.0	I	55 795.922901	0.000026	−0.000047	3
41624.0	I	55 803.957263	0.000025	−0.000020	3
41683.0	I	55 809.600444	0.000041	−0.000002	4
41903.0	I	55 830.642731	0.000025	−0.000016	2
42250.0	I	55 863.832200	0.000024	0.000013	3
42251.0	I	55 863.927831	0.000024	−0.000003	3
42461.0	I	55 884.013679	0.000025	0.000021	3
42596.0	I	55 896.925988	0.000024	0.000017	3

Notes. [†] (1) NSVS, (2) Ondřejov Observatory, (3) MONET/North, (4) Kolonica Observatory.

the eccentricity is $e_3 = 0.38 \pm 0.05$. The argument of periastron is $\varpi_{bin} = \varpi_3 - 180° = 26° \pm 2°$ and periastron passage occurred near JD 2 455 719 ($E \simeq 40738$) at O–C $\simeq$ 22 s. For the present model, a maximum of O–C $\simeq$ 67 s is predicted to occur near $E \simeq 44\,700$ in June 2012. With a binary mass of 0.617 $M_\odot$ (Drechsel et al. 2001), the semi-major axis of the third object is 3.52 AU and its mass is $M_3 = (31.5 \pm 1.0)/\sin i_3\ M_{Jup}$, very similar to the values quoted by Qian et al. (2010a). This mass is significantly lower than the estimate of Çamurdan et al. (2012). The present data provide no evidence of a deviation of the mid-eclipse times from those created by a single object, but the achievable accuracy of better than 1 s opens the prospect to searching for a fourth object, as found, e.g., in the WD/MS binary NN Ser (Beuermann et al. 2010).

3.3. Secondary eclipses

The present observations locate the secondary eclipse in NSVS1425 and HS0705 at orbital phases of $\phi = 0.5002 \pm 0.0002$ and $\phi = 0.4997 \pm 0.0003$, respectively. This finding along with the clearly non-sinusoidal form of the eclipse time variations excludes a sizeable contribution of apsidal motion (Todoran 1972) to the observed effect.

4. Discussion

We have presented evidence of eclipse time variations in NSVS1425 and HS0705, which are closely in line with variations expected from the light-travel time effect of a third body. The existence of companions orbiting PCEBs can no longer be easily refuted, although the cases of UX UMa and perhaps HU Aqr illustrate that there should be no indiscriminate application of the planetary model to all PCEBs showing eclipse time variations. In HS0705, the relatively short period of the third body of 8.4 yr and the large amplitude of 84 s will allow us to test the periodicity of the signal within the next decade, and confirmation will provide support for the third-body model. The often considered alternative of spin–orbit coupling, where star cycles change the spin of the secondary star and thereby the angular momentum of the binary orbit (Applegate 1992), remains a contender, but may be too feeble to account for the observed effects (e.g. Brinkworth et al. 2006; Chen 2009; Schwarz et al. 2009; Potter et al. 2011). Apsidal motion, can be safely excluded, at least for the objects studied here.

Given the large number of planets detected around single stars, it is unlikely that substellar objects do not exist in orbits around close binaries. The observational problem is to differentiate between the O–C variations caused by these companions and any effects intrinsic to the binary, which would require data covering many years. The fundamental questions then relate to the origin of such companions, which need not be the same for planet-sized and brown-dwarf objects, and to the incidence in different subtypes of PCEBs. With HW Vir (Lee et al. 2009), HS0705, and probably NSVS1425, at least three PCEBs with sdB primaries possess companions. For systems with a WD primary, the companions to NN Ser (Beuermann et al. 2010) and DP Leo (Qian et al. 2010b; Beuermann et al. 2011) appear reasonably well-established. Depending on the type of primary, these systems have different evolutionary histories (Zorotovic et al. 2011). For the former, the mass of the sdB star indicates that they are in the He-burning stage, having formed on the first giant branch. On the other hand, NN Ser and DP Leo contain CO-WDs and have formed on the asymptotic giant branch. The mass distribution of white dwarfs from the SDSS (Rebassa-Mansergas et al. 2012)[4] suggests that some PCEBs contain He-WDs and it will be interesting to find out whether these systems, too, contain companions, or more generally planetary systems, a finding that may shed some light on the origin of companions to PCEBs.

Acknowledgements. This work is based in part on data obtained with the MOnitoring NEtwork of Telescopes (MONET), funded by the Alfried Krupp von Bohlen und Halbach Foundation, Essen, and operated by the Georg-August-Universität Göttingen, the McDonald Observatory of the University of Texas at Austin, and the South African Astronomical Observatory. The "Astronomie & Internet" program of the Foundation and the MONET consortium provides a major fraction of the observation time to astronomical projects in high schools worldwide. The work of J.D. and his students at the Max-Planck-Gymnasium was supported by the Robert Bosch Foundation. The research of M.W. and P.Z. was supported by the Research Program MSM0021620860 of the Ministry of Education of the Czech Republic.

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