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A search for substellar objects orbiting the sdB eclipsing binary HS 0705+6700

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ABSTRACT

By using 78 newly determined timings of light minima together with those collected from the literature, we analysed the changes in the observed minus calculated (O−C) diagram in HS 0705+6700, a short-period (2.3 h) eclipsing binary that consists of a very hot subdwarf B-type (sdB) star and a very cool fully convective red dwarf. We confirmed the cyclic variation in the O−C and refined the parameters of the circumbinary brown dwarf (reported to orbit the binary system in 2009) by analysing the changes for the light travel time effect that arises from the gravitational influence of the third body. Our results indicate the lower mass limit of the third body to be $M_3 \sin i' = 33.7(\pm 1.6)\,M_{\rm Jup}$. This companion would be a brown dwarf if its orbital inclination is larger than 27°.7 and it is orbiting the central eclipsing binary with an eccentricity $e \sim 0.2$ at a separation of about 3.7(±0.1) au.

Key words: binaries: close – binaries: eclipsing – brown dwarfs – stars: individual: HS 0705+6700 – subdwarfs.

1 INTRODUCTION

HW Vir-type stars are a group of eclipsing binaries that consist of very hot subdwarf stars and cool M-type stars with periods between 2 and 3 h. To date, only about 12 such systems were discovered (e.g. Menzies & Marang 1986; Kilkenny et al. 1998; Drechsel et al. 2001; Östensen et al. 2007, 2010; Polubek et al. 2007; Wils, Di Scala & Otero 2007; Geier et al. 2011; Barlow et al. 2013; Schaffenroth et al. 2013). The subdwarf B-type (sdB) components in this group of binaries are on the extreme horizontal branch of the Hertzsprung–Russell diagram with a mass of about 0.47 $M_\odot$. They are burning helium in their cores and have very thin hydrogen envelopes. These systems are thought to be the products of common-envelope (CE) evolution resulting from dynamically unstable mass transfer near the tip of the red giant branch (e.g. Han et al. 2003) and will evolve into normal cataclysmic variables through angular momentum loss via magnetic braking and gravitational radiation (e.g. Shimansky et al. 2006). Recently, substellar companions (i.e. brown dwarfs and extrasolar planets) to HW Vir-type binaries were found (Kilkenny, van Wyk & Marang 2003; Qian et al. 2008, 2009b, 2012b; Lee et al. 2009; Almeida, Jablonski & Rodrigues 2013). These discoveries have revived interest in these binary stars.

Because of the large temperature differences between the two components and their compact structures, both primary and secondary eclipses of HW Vir binaries are short and well defined; the light curves show a strong reflection effect with very deep primary and shallow secondary minima. Therefore, especially times of the primary light minimum can be determined with a high precision (e.g. Kilkenny, Marang & Menzies 1994; Kilkenny et al. 2000), and very small amplitude cyclic changes in the observed minus calculated (O−C) diagram can be detected. These small-amplitude cyclic variations may be caused by the presence of a planet or a brown dwarf tertiary object via the light travel time effect. Some examples recently discovered by our group are those orbiting the magnetic cataclysmic variables DP Leo and HU Aqr (Qian et al. 2010c, 2011) and the detached white dwarf binaries QS Vir and RR Cae (Qian et al. 2010b, 2012a). To search for substellar companions and to investigate the formation and evolution of HW Vir-like binary stars, we started to monitor them since 2006 (e.g. Qian et al. 2009a,b; Zhu & Qian 2010; Zhu et al. 2011).

With an orbital period of 2.3 h, HS 0705+6700 (=GSC 4123−265) is one of the HW Vir-type binary stars. It was found as a hot subdwarf candidate by the Hamburg Schmidt

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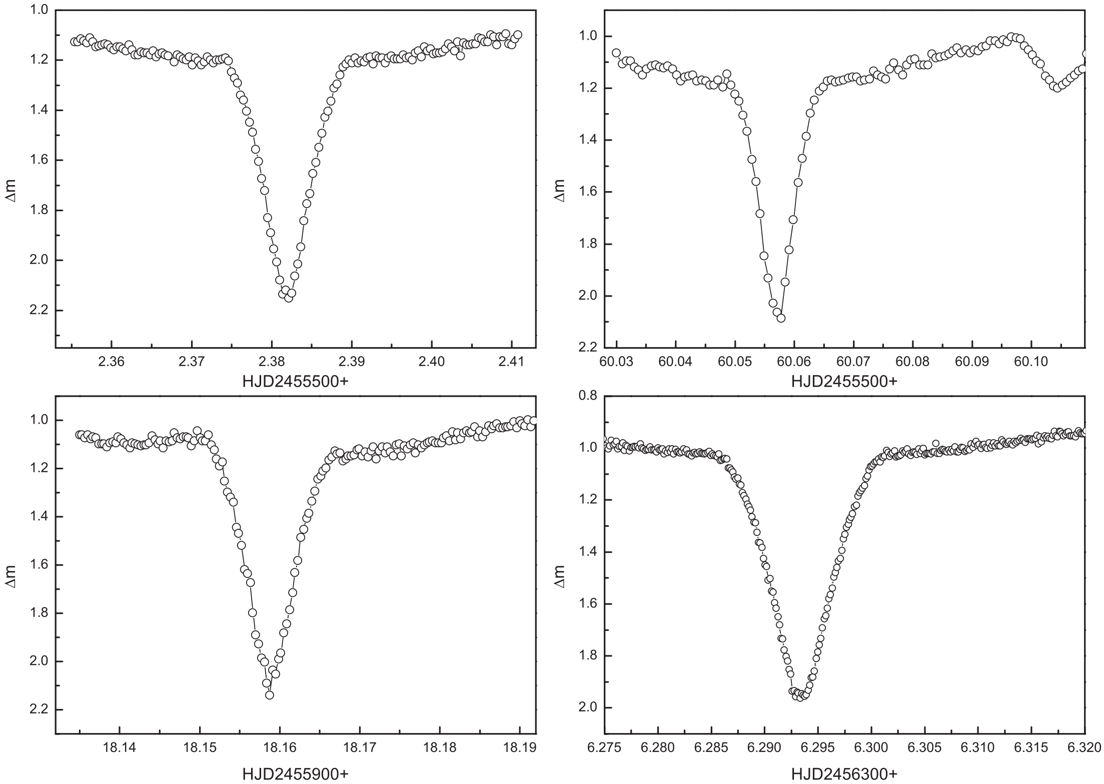

Figure 1. Several eclipse profiles of HS 0705+6700 observed by using the 1.0 m and the 85 cm telescopes on 2010 November 1 and December 29, 2011 November 22 and 2013 January 13, respectively.

survey (Hagen et al. 1995) and further spectroscopic data by Heber et al. (1999) and Edelmann et al. (2001) indicated that its effective temperature lies in the predicted pulsating instability strip. Later, this star was included in a photometric monitoring programme at the Nordic Optical Telescope (see Östensen et al. 2001a,b) to search for pulsations but the photometric observations revealed that this star was an eclipsing binary. A detailed photometric and spectroscopic investigation by Drechsel et al. (2001) suggested that HS 0705+6700 was a detached, short-period eclipsing binary containing a hot sdB primary star and a cool M-type secondary revealing that it was the third one of the small group of HW Vir-type binaries.

The orbital period of HS 0705+6700 was first determined to be 0.095 646 65 d by Drechsel et al. (2001). Qian et al. (2009a) discovered a cyclic change in the O−C curve that revealed the presence of a possible brown dwarf companion in this system. The period change of the binary system was later investigated by Qian et al. (2010a), Çamurdan, Zengin Çamurdan & Ibanoğlu (2012) and Beuermann et al. (2012). Qian et al. (2010a) pointed out that apart from the cyclic change there is a long-term decrease in the orbital period. The analysis by Çamurdan et al. (2012) showed that the third body may be a cool stellar object. The mass of the circumbinary brown dwarf was most recently revised by Beuermann et al. (2012) as $M_3 \sin i' = 31.5(\pm 1.0)\ M_{\rm Jup}$ orbiting the central binary in an eccentric orbit ($e = 0.38$) at a separation of about 3.52 au. In this paper, we present 78 more eclipse times for HS 0705+6700 that confirm the presence of the tertiary object and the longer time spanning data further refine its orbital parameters. Analysing the new set of O−C data, we found a possibility of a quadratic term in the form of upward parabola to be superimposed on the cyclic variations.

2 NEW OBSERVATIONS AND THE CHANGES OF THE O−C CURVE

The photometric monitoring of HS 0705+6700 started in 2006 December and some of the eclipse times were published by Qian et al. (2009a, 2010a). A cyclic change in the O−C diagram, that may reveal the presence of a circumbinary brown dwarf, was discovered by Qian et al. (2009a). To confirm the presence of the substellar object and investigate its properties, we continued to monitor the eclipsing binary. The telescopes we used were: the 60 cm and the 1.0 m telescopes in YunNan Observatories (YNO); the 85 cm and the 2.16 m telescopes at the Xinglong station of the National Astronomical Observatories (NAO); and the 60 cm Mt Suhora telescope and the 50 cm Krakow telescope in Poland. Several eclipse profiles obtained with the 1.0 m and the 85 cm telescopes are shown in Fig. 1. Observations at all sites were done with ccd cameras equipped with Johnson wide-band *UBVRI* filters. Data were also taken with red blocking *BG*40 and luminance (*L*) filters and without any filter (these observations are marked by a dash in Table 1) to have higher S/N ratio. Frames have been reduced for bias, dark and flat-field taken every night, usually on sky, using the IRAF package. The differential photometry was performed with the CMUNIPACK software, which is an interface for the well-known DAOPHOT program. Such processed data around the minima were next used for a minimum time determination which was predominantly done using the Kwee & van Woerden (1956) method. Only if a minimum coverage was not dense enough to apply the Kwee & van Woerden method, we determined its timing by fitting a parabola with the least-squares method. The errors listed in Table 1 are those derived from the Kwee & van Woerden and the least-squares methods. In total, 78 new times of light minimum were obtained. Since Barycentric

Table 1. Our CCD timings of light minimum for HS 0705+6700.

HJD−240 0000 (d)	BJD−240 0000 (d)	Errors (d)	Min.	Filters	Telescopes[a]
54 845.384 52	54 845.385 31	0.000 18	I	*L*	Krakow50
54 845.384 40	54 845.385 18	0.000 27	I	*BG*40	Suhora60
54 895.311 90	54 895.312 68	0.000 29	I	*L*	Krakow50
54 895.311 80	54 895.312 59	0.000 32	I	*L*	Krakow50
54 896.029 19	54 896.029 98	0.000 44	II	*R*	Xinglong85
54 912.432 84	54 912.433 63	0.000 16	I	*R*	Suhora60
54 926.301 77	54 926.302 56	0.000 15	I	*R*	Suhora60
54 926.397 15	54 926.397 93	0.000 13	I	*R*	Suhora60
54 941.318 40	54 941.319 18	0.000 31	I	*BG*40	Krakow50
54 946.578 68	54 946.579 47	0.000 13	I	*BG*40	Krakow50
54 950.021 85	54 950.022 63	0.000 11	I	*R*	Xinglong85
54 957.051 67	54 957.052 45	0.000 10	II	*R*	Xinglong85
55 025.391 78	55 025.392 56	0.000 40	I	*BG*40	Krakow50
55 051.503 16	55 051.503 94	0.000 24	I	*BG*40	Krakow50
55 053.511 92	55 053.512 71	0.000 24	I	*BG*40	Krakow50
55 063.363 11	55 063.363 89	0.000 16	I	*BG*40	Krakow50
55 090.431 16	55 090.431 95	0.000 03	I	*L*	Suhora60
55 102.291 38	55 102.292 16	0.000 02	I	*BG*40	Krakow50
55 126.489 99	55 126.490 77	0.000 02	I	*BG*40	Suhora60
55 138.254 46	55 138.255 24	0.000 04	I	*BG*40	Suhora60
55 151.118 96	55 151.119 75	0.000 09	II	*V*	Xinglong85
55 152.410 25	55 152.411 03	0.000 01	I	*BG*40	Suhora60
55 164.653 04	55 164.653 82	0.000 02	I	–	Suhora60
55 206.259 40	55 206.260 18	0.000 03	I	*B*	Xinglong216
55 221.467 23	55 221.468 01	0.000 02	I	*R*	Suhora60
55 231.605 76	55 231.606 54	0.000 01	I	*R*	Suhora60
55 259.534 60	55 259.535 38	0.000 02	I	*R*	Suhora60
55 264.316 97	55 264.317 75	0.000 01	I	*BG*40	Krakow50
55 268.047 22	55 268.048 00	0.000 04	I	*B*	Xinglong85
55 288.324 31	55 288.325 09	0.000 02	I	*R*	Krakow50
55 293.011 01	55 293.011 79	0.000 07	I	*V*	Xinglong85
55 293.011 13	55 293.011 91	0.000 09	I	*R*	Xinglong85
55 293.058 73	55 293.059 51	0.000 09	II	*V*	Xinglong85
55 293.058 94	55 293.059 72	0.000 14	II	*R*	Xinglong85
55 353.459 72	55 353.460 50	0.000 04	I	*BG*40	Krakow50
55 473.400 95	55 473.401 72	0.000 01	I	–	Krakow50
55 479.522 32	55 479.523 10	0.000 01	I	*R*	Suhora60
55 509.364 14	55 509.364 91	0.000 06	I	*R*	Xinglong85
55 535.380 10	55 535.380 87	0.000 02	I	*R*	Suhora60
55 560.057 05	55 560.057 82	0.000 06	I	*R*	Xinglong85
55 562.400 41	55 562.401 18	0.000 08	II	*R*	Xinglong85
55 567.613 07	55 567.613 84	0.000 02	I	*R*	Suhora60
55 621.462 28	55 621.463 05	0.000 01	I	*V*	Suhora60
55 646.999 86	55 647.000 63	0.000 10	I	*I*	Xinglong85
55 654.077 84	55 654.078 61	0.000 04	I	*R*	Xinglong85
55 694.058 25	55 694.059 02	0.000 03	I	–	Xinglong85
55 740.446 99	55 740.447 75	0.000 02	I	*BG*40	Krakow50
55 785.401 01	55 785.401 78	0.000 02	I	*BG*40	Krakow50
55 836.285 15	55 836.285 92	0.000 02	I	*R*	Suhora60
55 875.404 63	55 875.405 39	0.000 09	I	*R*	Xinglong85
55 878.178 48	55 878.179 25	0.000 04	I	*R*	Krakow50
55 878.274 08	55 878.274 84	0.000 04	I	*R*	Krakow50
55 905.150 89	55 905.151 65	0.000 08	I	–	Xinglong85
55 915.193 82	55 915.194 58	0.000 05	I	–	YNO60
55 918.158 85	55 918.159 61	0.000 05	I	–	YNO100
55 924.567 19	55 924.567 95	0.000 01	I	*R*	Suhora60
55 928.297 49	55 928.298 25	0.000 11	I	–	YNO60
55 933.271 10	55 933.271 86	0.000 05	I	–	YNO100
55 938.053 59	55 938.054 35	0.000 17	I	–	YNO60
55 958.330 47	55 958.331 23	0.000 01	I	*BG*40	Krakow50
55 966.269 13	55 966.269 89	0.000 04	I	*R*	Krakow50
56 007.110 27	56 007.111 03	0.000 10	I	*R*	Xinglong85
56 031.021 87	56 031.022 63	0.000 10	I	*R*	Xinglong85
56 056.464 14	56 056.464 90	0.000 02	I	*BG*40	Krakow50
56 072.054 54	56 072.055 30	0.000 10	I	*R*	Xinglong85
56 108.495 92	56 108.496 68	0.000 02	I	*BG*40	Krakow50
56 121.503 89	56 121.504 66	0.000 01	I	*R*	Suhora60
56 181.474 39	56 181.475 16	0.000 02	I	*BG*40	Krakow50
56 212.368 30	56 212.369 07	0.000 02	I	*R*	Suhora60
56 216.385 27	56 216.386 04	0.000 09	I	–	YNO60
56 219.254 76	56 219.255 53	0.000 08	I	–	YNO100
56 223.271 83	56 223.272 60	0.000 08	I	–	YNO100
56 234.367 09	56 234.367 86	0.000 07	I	–	YNO60
56 239.340 87	56 239.341 64	0.000 14	I	*R*	Xinglong216
56 240.297 21	56 240.297 98	0.000 07	I	*R*	Xinglong216
56 241.253 55	56 241.254 32	0.000 09	I	–	YNO60
56 252.252 94	56 252.253 71	0.000 08	I	–	YNO60
56 255.217 98	56 255.218 75	0.000 09	I	–	YNO60
56 275.303 93	56 275.304 70	0.000 10	I	–	YNO60
56 294.241 86	56 294.242 63	0.000 03	I	*R*	Krakow50
56 297.206 88	56 297.207 65	0.000 10	I	–	YNO60
56 330.109 42	56 330.110 19	0.000 08	I	–	YNO60
56 362.055 30	56 362.056 07	0.000 06	I	–	YNO100
56 365.116 21	56 365.116 98	0.000 08	I	–	Xinglong85
56 367.076 84	56 367.077 61	0.000 19	II	–	YNO100
56 373.054 84	56 373.055 61	0.000 20	I	–	YNO60
56 380.132 63	56 380.133 40	0.000 09	I	–	Xinglong85
56 401.461 83	56 401.462 60	0.000 02	I	*R*	Suhora60
56 404.426 80	56 404.427 57	0.000 02	I	*R*	Suhora60
56 409.304 82	56 409.305 58	0.000 01	I	*BG*40	Suhora60
56 432.355 55	56 432.356 31	0.000 02	I	*R*	Suhora60

[a]Krakow50: the 50 cm Krakow telescope in Poland; Suhora60: the 60 cm Mt Suhora telescope in Poland; Xinglong85: the 85 cm telescopes in Xinglong station; Xinglong216: the 2.16 m telescopes in Xinglong station; YNO60: the 60 cm telescope in YNO; YNO100: the 1.0 m telescope in YNO.

Dynamical Julian Date (BJD) is a precise time system, it was applied during our analysis. The HJD times of light minimum were converted to BJD with the code of Stumpff (1980) and those eclipse times (in both the HJD and BJD) are shown in Table 1. The BJD values of the times of light minimum published by Qian et al. (2010a) are also included in the table.

Drechsel et al. (2001) obtained 13 eclipse times of HS 0705+6700 and derived the following linear ephemeris,

$$\mathrm{Min.}I = \mathrm{BJD}\,2451\,822.760\,549 + 0.095\,646\,65 \times E, \quad (1)$$

where BJD 2451 822.760 549 is the initial epoch and 0.095 646 65 is the orbital period. Later, some times of light minimum were published by Niarchos, Gazeas & Manimanis (2003), Németh, Kiss & Sárneczky (2005), Kruspe, Schuh & Traulsen (2007), Qian et al. (2009b, 2010a), Çamurdan et al. (2012) and Beuermann et al. (2012). The $(\mathrm{O-C})_1$ values of all available times of light minimum were calculated by using the ephemeris from equation (1). The corresponding $(\mathrm{O-C})_1$ diagram is shown in Fig. 2 where blue solid dots refer to our 78 times of light minimum, while green solid dots to other eclipse times collected from the literature.

To revise the parameters of the substellar companion, we analyse the $(\mathrm{O-C})_1$ curve for the light travel time effect. By considering a general case (an eccentric orbit; e.g. Irwin 1952), the $(\mathrm{O-C})_1$ diagram was described by the following equation (without a quadratic term),

$$(\mathrm{O-C})_1 = \Delta T_0 + \Delta P_0 \times E + \tau, \quad (2)$$

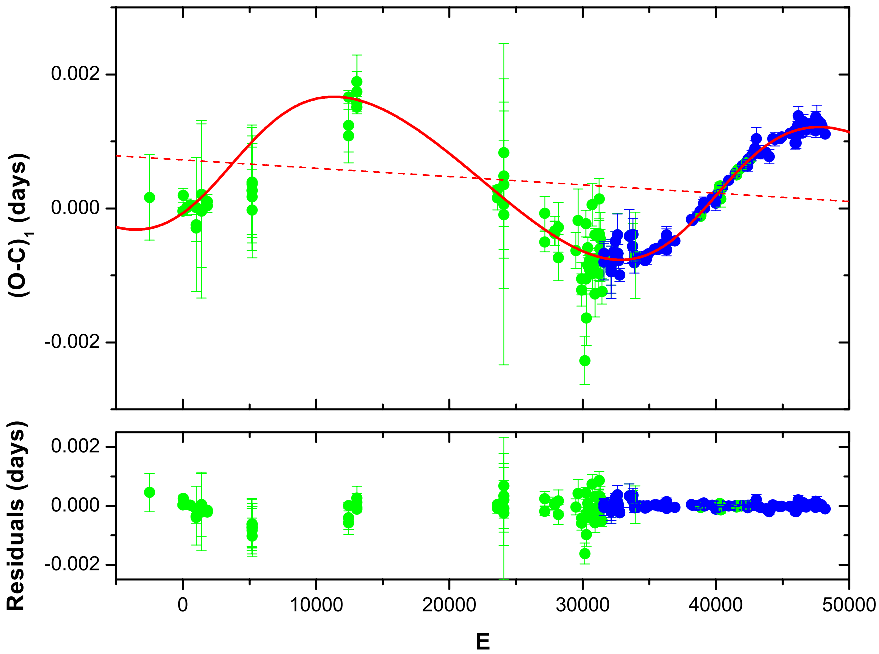

Figure 2. (O − C)$_1$ diagram with respect to the linear ephemeris in equation (1). Green solid dots refer to the data collected from the literature, while those in blue to our new observations monitored since 2008. The dashed red line in the upper panel represents the revision of the linear ephemeris and the solid one is the combination of a cyclic change and the revision. The residuals calculated with equation (2) are shown in the lower panel where more significant deviations are seen for the observations made before E=15 000.

Table 2. Orbital parameters of the third body.

Parameters	Without quadratic term	With quadratic term
Revised epoch, ΔT_0(d)	+0.000 723(±0.000 065)	0.000 984(±0.000 061)
Revised period, ΔP_0(d)	$-1.24(\pm0.17) \times 10^{-8}$	$-3.93(\pm0.51) \times 10^{-8}$
Rate of the period change, $\dot{P}$(d yr^{-1})	0.0	$+9.8(\pm2.2)\times 10^{-9}$
Eccentricity, e	0.22(±0.02)	0.19(±0.03)
Longitude of the periastron passage, ω(°)	352.9(±5.7)	358.1(±7.3)
Periastron passage, T	2452 127.33(±68.03)	2452 397.69(±117.37)
The semi-amplitude, K (d)	0.001 114(±0.000 012)	0.001 012(±0.000 029)
Orbital period, P_3 (yr)	9.53(±0.10)	8.87(±0.23)
Projected semimajor axis, $a_{12}\sin i'$ (au)	0.193(±0.002)	0.175(±0.005)
Mass function, $f(m)$(M$_\odot$)	$7.9(\pm0.3) \times 10^{-5}$	$6.9(\pm0.6) \times 10^{-5}$
Mass of the third body, $M_3\sin i'$ (M$_\odot$)	0.0322(±0.0006)	0.0306(±0.0015)
Orbital separation, $d_3(i' = 90°)$ (au)	3.7(±0.1)	3.5(±0.2)
The sum of squared residuals, χ^2	0.0397	0.0379

where ΔT_0 and ΔP_0 are the revised epoch and period with respect to the ephemeris values in equation (1). τ is the cyclic change caused by the light travel time effect due to the presence of the tertiary object, i.e.

$$\tau = K\left[(1-e^2)\frac{\sin(\nu+\omega)}{1+e\cos\nu}+e\sin\omega\right]$$
$$= \Delta T_0+\Delta P_0\times E+K\left[\sqrt{1-e^2}\sin E^*\cos\omega+\cos E^*\sin\omega\right], \quad (3)$$

where ν is the true anomaly, E^* is the eccentric anomaly, $K = \frac{a_{12}\sin i'}{c}$ ($a_{12}\sin i'$ is the projected semimajor axis). When solving equation (2), the following two dependences,

$$N = E^* - e\sin E^* \quad (4)$$

and

$$N = \frac{2\pi}{P_3}(t-T) \quad (5)$$

were used, where N is the mean anomaly and t is the time of a light minimum. The other parameters and the derived values are listed in Table 2. A weighted least-squares method was used to obtain the best solution. The reciprocal of the square of the error was taken as the weight of each data point. The result indicates that the (O − C)$_1$ curve shows a cyclic change with a period of about 9.53 yr. The corresponding value of χ^2 (the sum of squared residuals) is about 0.0397.

Finally, we checked how much the solution could be improved if a quadratic term, instead of a linear one only, is included in equation (2), i.e.

$$(\mathrm{O-C})_1 = \Delta T_0 + \Delta P_0 \times E + \beta E^2 + \tau. \quad (6)$$

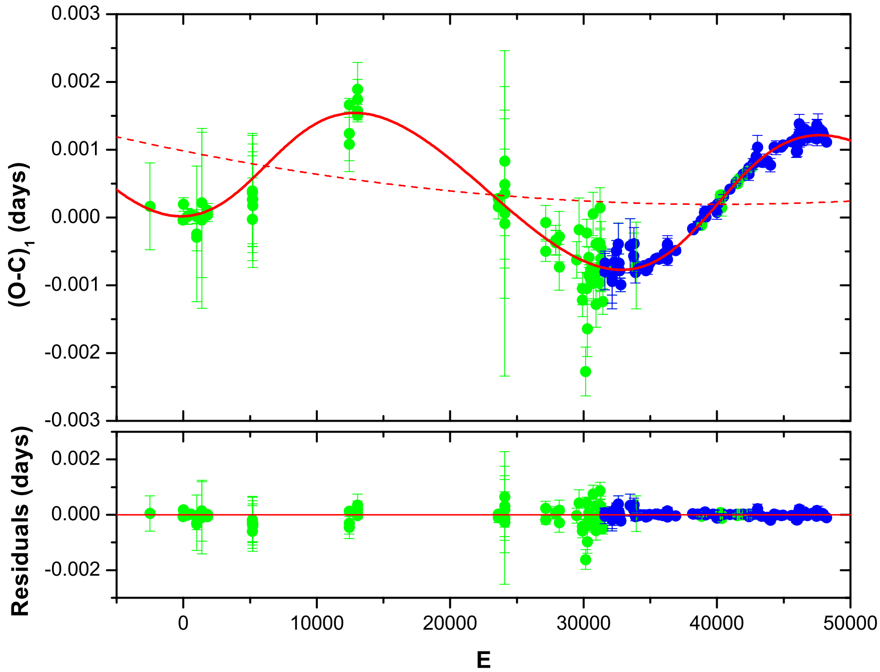

Figure 3. The same as those in Fig. 2, but a quadratic term was included to fit the $(O-C)_1$ curve. The solid line in the panel refers to a combination of an upward parabolic variation and a cyclic change. The dashed line represents the upward parabolic variation that reveals a continuous increase of the orbital period. After both the upward parabolic change and the cyclic variation were removed, the residuals are plotted in the lower panel.

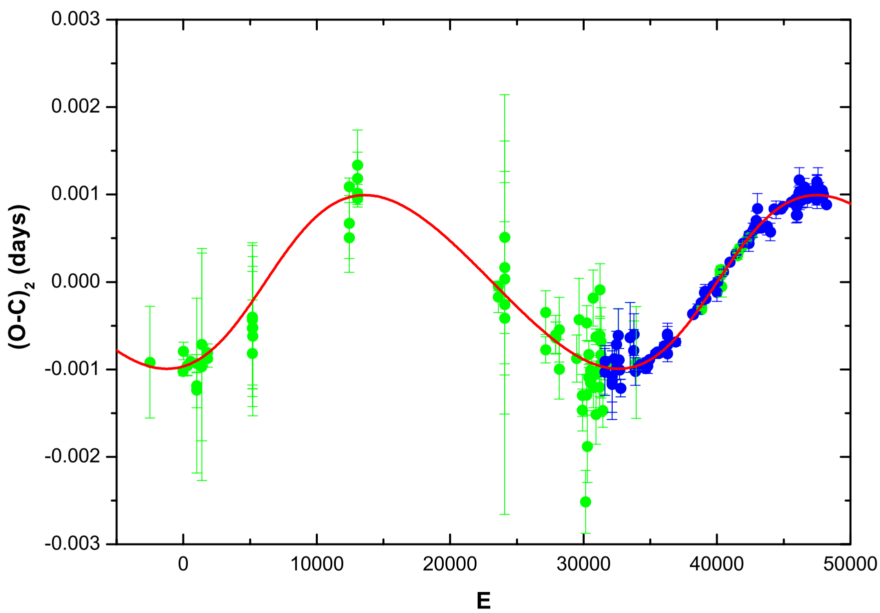

Figure 4. The $(O-C)_2$ values with respect to the quadratic part of equation (3) are displayed where a cyclic change is more clearly seen. Symbols are the same as in Figs 2 and 3.

The fit turned out to be somewhat better ($\chi^2 = 0.0379$), especially for the oldest data. The results for the best solution derived with equation (6) are also listed in Table 2 and the resulting theoretical curves, a combination of cyclic and quadratic variations, are shown in Fig. 3 (upper panel) while residuals with respect to equation (6) are plotted in the bottom panel. Introduction of the quadratic term resulted in a lower value of cyclic variations period (about 8.87 yr). The light travel time effect amplitude within this solution is 0.001 012 d (or 87.4 s). The quadratic term in equation (6) would require a period increase at a rate of $\dot{P} = +9.8 \times 10^{-9}\,\mathrm{d\,yr^{-1}}$. After the quadratic term was subtracted, the $(O-C)_2$ diagram is displayed in Fig. 4.

3 DISCUSSIONS AND CONCLUSIONS

By monitoring HS 0705+6700 with several telescopes in Poland and China, 78 times of light minimum were obtained. Our data cover nearly half of the orbital period of the circumbinary brown dwarf proposed by Qian et al. (2009). When combined with older measurements, the O−C data cover more than one revolution of the companion. To refine the orbital parameters of the proposed circumbinary brown dwarf, the cyclic change was analysed for light travel time effect. We confirmed that the O−C diagram of HS 0705+6700 shows a cyclic change and improved its period to be 9.53 yr and an amplitude of 0.001 114 d (96.3 s). The orbital eccentricity was derived as $e = 0.22$, that is smaller than that ($e = 0.38$) determined by Beuermann et al. (2012).

The projected radius of the orbit of HS 0705+6700 rotating around the barycentre of the triple system was computed with the equation

$$a'_{12} \sin i' = K \times c, \tag{7}$$

where K is the amplitude of the cyclic change and c is the speed of light. Then, by using the absolute parameters determined by Drechsel et al. (2001), a calculation with the following equation,

$$f(m) = \frac{4\pi^2}{GP_3^2} \times (a'_{12} \sin i')^3 = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2}, \tag{8}$$

where G and P_3 are the gravitational constant and the period of the $(\mathrm{O - C})_2$ oscillation, leads to the mass function and the lower limit mass of the HS 0705+6700 companion as: $f(m) = 7.9(\pm 0.6) \times 10^{-5}\,\mathrm{M}_\odot$ and $M_3 \sin i' = 0.0322(\pm 0.0006)\,\mathrm{M}_\odot = 33.7(\pm 1.6)\,M_{\mathrm{Jup}}$, respectively. The solution with a quadratic term results in the following parameters: $f(m) = 6.9(\pm 0.6) \times 10^{-5}\,\mathrm{M}_\odot$ and $M_3 \sin i' = 0.0306(\pm 0.0015)\,\mathrm{M}_\odot = 32.0(\pm 1.6)\,M_{\mathrm{Jup}}$, respectively. If the orbital inclination of the tertiary object is larger than 27°.7, its mass corresponds to $M_3 \leq 0.072\,\mathrm{M}_\odot$, the limit for a brown dwarf. If the quadratic term is considered, the inclination limit would be 26°.3. Therefore, with about 69 per cent probability, the third body is a brown dwarf (assuming a random distribution of orbital plane inclinations). Its parameters, listed in Table 2, are close to those determined by Qian et al. (2009) and by Beuermann et al. (2012). When the orbital inclination of the third body equals to 90°, the orbital separation between the brown dwarf object and the central binary is about 3.7(±0.1) au for the linear term solution and about 3.5(±0.2) au for the quadratic term one.

The upward parabolic variation in the upper panel of Fig. 3, if real, would indicate that the period of HS 0705+6700 is increasing at a rate of $\dot{P} = +9.8 \times 10^{-9}\,\mathrm{d\,yr^{-1}}$. Since HS 0705+6700 is a detached binary system, where both components are well within their Roche lobes, no Roche lobe-filling mass transfer occurs between them. Moreover, the angular momentum loss caused by gravitational radiation or/and magnetic braking should cause a decrease of the orbital period. Therefore, neither mass transfer nor angular momentum loss can explain the period increase of HS 0705+6700. As in the case of the eclipsing white dwarf binary RR Cae (Qian et al. 2012a), the observed upward parabolic variation might be a part of another very long-period cyclic change as a result of the light travel time effect due to the presence of a circumbinary substellar object in a very wide orbit.

HS 0705+6700 was formed through a CE after the more massive component star in the original system evolved into a red giant. The ejection of the CE removed a large amount of angular momentum, and then the short-period close binary was formed that contains an sdB-type star with a very thin hydrogen envelope. The confirmation of two possible substellar companions in HS 0705+6700 will shed light on the origin of this type of objects as well as on the interaction between red giants and their companions. To confirm the existence of the outer substellar object, many more times of light minimum are required in the future.

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