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DISCOVERY OF AN SU UMA-TYPE ECLIPSING CATACLYSMIC VARIABLE STAR INSIDE THE CV "PERIOD GAP"

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Abstract

We report the discovery of CzeV404 – eclipsing cataclysmic variable star apparently of SU UMa-type with orbital period inside the period gap. Using photometric observations taken during 15 nights from June to September 2012 and 8 nights from July to August 2013 we measured orbital period 2.35 hours and superhump period 2.50 hours. From the observed period excess, we estimate the mass ratio of the system $q = 0.30$.

Introduction

SU UMa-type cataclysmic variable stars consists of close pair of a white dwarf (primary) and a main sequence (secondary) star. The secondary star fills the Roche-lobe, which causes a mass transfer to the primary star, creating an accretion disc (providing the magnetic field of the primary star is not strong enough to prohibit building up of the accretion disc). A hot spot is formed on the accretion disc, where the stream of mass from the secondary star intersects the disc's outer edge. Thermal-instability in the accretion disc causes semi-periodic brightenings (outbursts).

SU UMa-type CV orbital periods span a range from approx. 80 minutes up to tens of hours, with a distinct gap between 2 and 3 hours. Orbital period decreases through the CV evolution due to angular momentum loses (e.g. by magnetic braking). When the orbital period reaches approx. 3 hours, the secondary star becomes fully convective through the mass loss, shrinks inside its Roche-lobe and mass transfer to the primary star is significantly reduced. Outbursts stop to occur and the particular CV becomes undetectable. Mass transfer is restored again when the orbital period decreases to approx. 2 hours by gravitational radiation and the secondary star fills its Roche-lobe again (e.g. Howell et al., 2001).

Observations

CzeV404 (USNO-A2.0 0975-11872373, $\alpha_{2000} = 18^{\mathrm{h}}30^{\mathrm{m}}1\overset{\mathrm{s}}{.}833$, $\delta_{2000} = +12^{\circ}33'47\overset{''}{.}43$) was found on a series of wide-field CCD exposures of a field in Hercules acquired on 22$^{\mathrm{th}}$ July, 2012. The light curve showed two eclipses approx. 2.35 hours apart and prominent brightness peaks preceding each eclipse, indicating an accretion disc hot spot. All these light curve features suggest previously unknown eclipsing CV star.

CzeV404 was discovered and observed using G4-16000 CCD camera on 0.25 m f/5.4 Newtonian telescope. Each image has $71'\times71'$ field of view with sampling $1\overset{''}{.}39$/pixel.

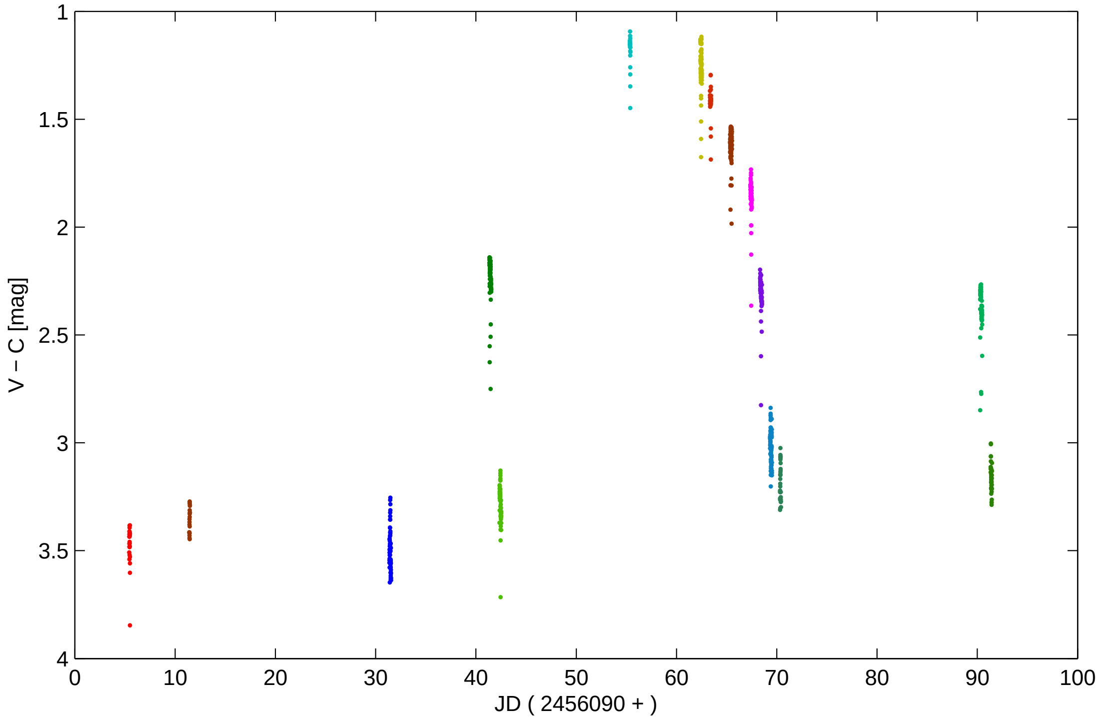

Figure 1. CzeV404 observations spanning June to September, 2012.

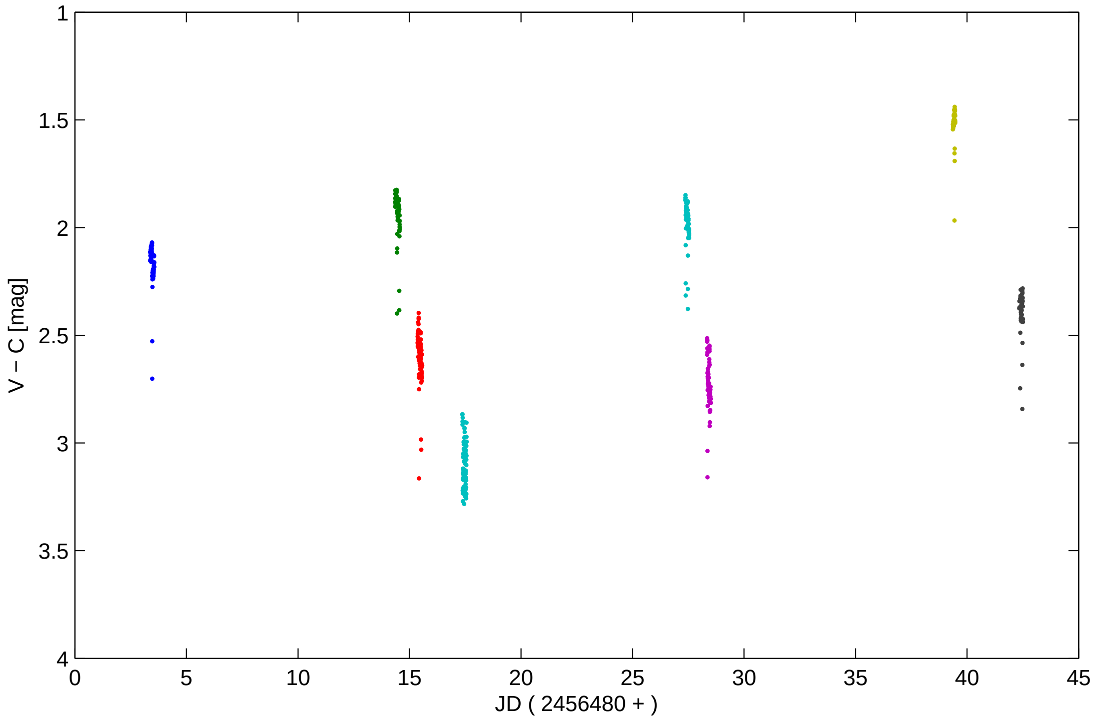

Figure 2. CzeV404 observations spanning June to August, 2013.

Individual unfiltered exposures were 240 s or 180 s long, depending on seeing and transparency on the particular observing night.

Another star within the field of view (GSC 01031-01228) with similar brightness and color index was chosen as a comparison star to correct for atmospheric extinction. Beside the CzeV404, 55 other variable stars and variable star suspects were observed within the field of view. The selected comparison star is one of the eight carefully chosen comparison stars in the field of view, selected according to B-V index to correspond to the B-V indexes of individual observed stars. Six observed variable stars out of total 56 stars were compared with the above mentioned comparison stars.

Images were acquired using the SIPS software package. All exposures were calibrated with appropriate dark frames and flat fields, that were created as a median of five individual dark and flat exposures. Photometry was processed using the C-munipack software package (Motl, 2004).

Our light curve shows that CzeV404 exhibits outbursts from the quiescent magnitude of about 16.7 mag. We observed two types of outbursts: short ones lasting couple days (on JD 2456132 and JD 2456181) and one longer and brighter outburst lasting about 15 days with peak brightness of 14.4 mag, which occurred between JD 2456145 and JD 2456160 (figure 1). This light curve is compatible with an SU UMa-type CV, which exhibits normal outbursts and superoutbursts.

We observed significant changes in the light curve shape in phases that we identified as outburst and superoutburst (figure 3).

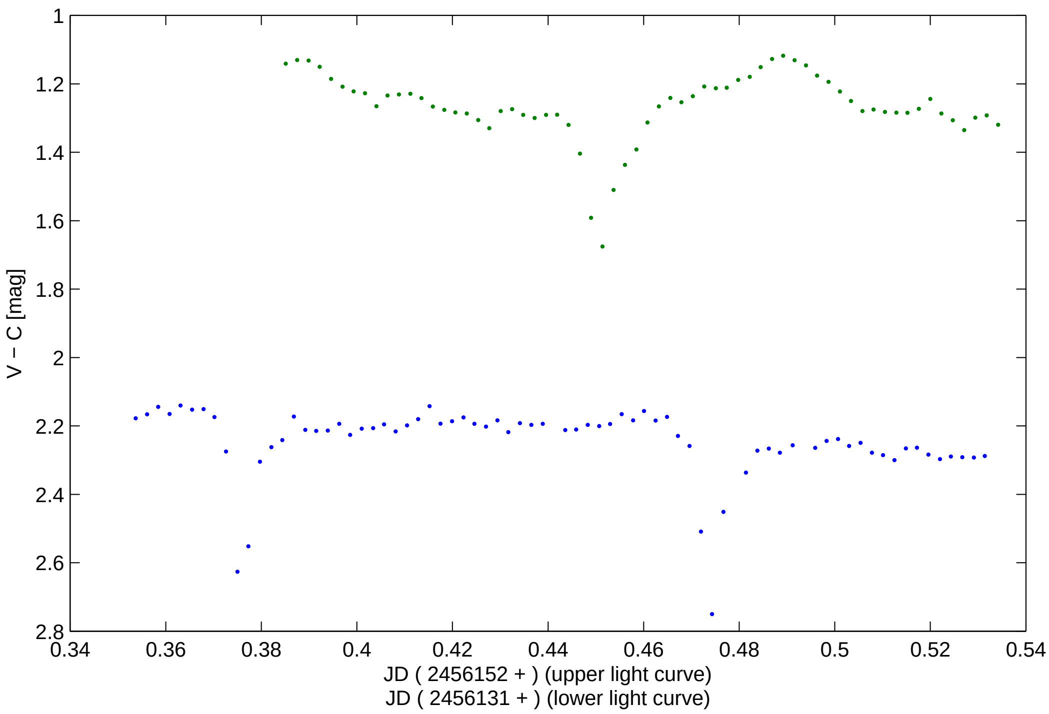

Figure 3. CzeV404 light curves during outburst on 22$^{\rm th}$ July, 2012 (lower light curve) and during superoutburst on 12$^{\rm th}$ August, 2012 (upper light curve).

In the outburst phase the CzeV404 light curve showed brightenings just before eclipse, caused by accretion disc hot spot. This brightening disappeared during superoutburst phase, but we observed periodic oscillations with a period close but not identical to the orbital period. We have identified these oscillations as superhumps with the period ~ 0.1 days. This further strengthens the classification of CzeV404 as an SU UMa-type CV[1]. More details about superhumps are given in Section Results.

The photometry measurements are affected by a nearby star, just around 3.6 pixels ($\sim$ 5 arc seconds) apart (see the left panel on figure 4 and figure 5). The nearby star brightness was not measured due to close proximity of both stars, but it is somewhat weaker than CzeV404 in the quiescence state. The aperture used to determine CzeV404 brightness is 5 pixels in diameter, so the nearby star slightly affects the measured CzeV404 flux. We carefully checked that the variable star is indeed the object marked (1) on the left panel of figure 4.

Image from DSS2 Red survey and especially hi-resolution image acquired with the 0.65 m telescope of the Ondřejov Observatory (Astronomical Institute of the Czech Academy of Sciences) with $0\farcs5$/pixel sampling show three weak stars in close angular proximity to CzeC404 (see the right panel on the figure 5). However, the weak star to the north of the CzeV404 is outside of the photometric aperture and while the weak star to the west of the CzeV404 is projected to the aperture, its brightness is so low that it cannot be traced on individual frames from the photometric telescope, so we consider its effect to photometry negligible.

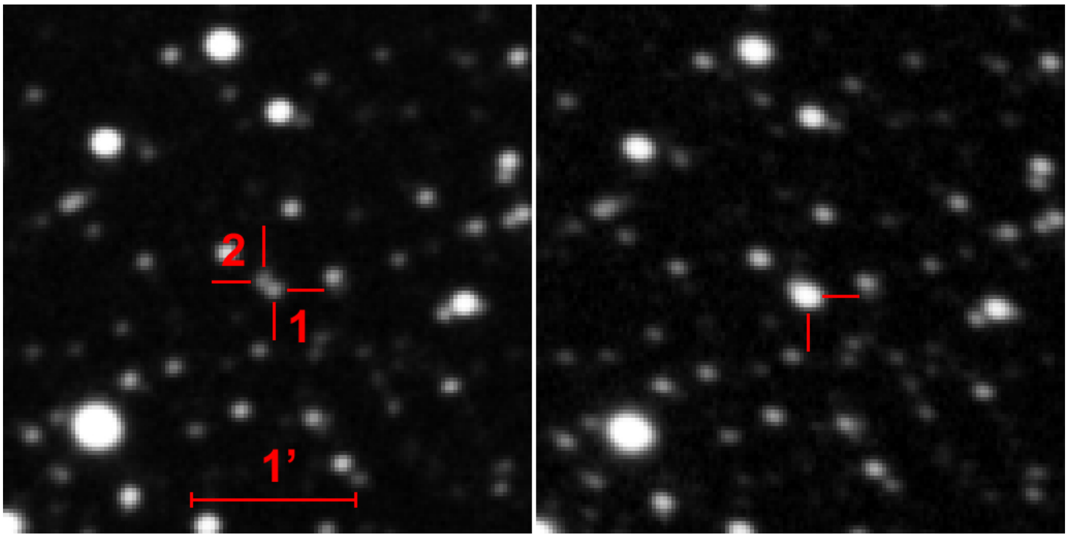

Figure 4. Left panel: CzeV404 (1) in quiescence state and a nearby star approx. 5"apart to the north-east (2) on 12th July 2012. Right panel: The same field with CzeV404 captured during superoutburst on 5th August 2012. Star shapes are slightly distorted due to aberrations of used wide-field optics. Both panels are cropped from the original photometry telescope field of view, the image scale is $1\farcs39$/pixel.

[1]http://www.sai.msu.su/gcvs/gcvs/iii/vartype.txt

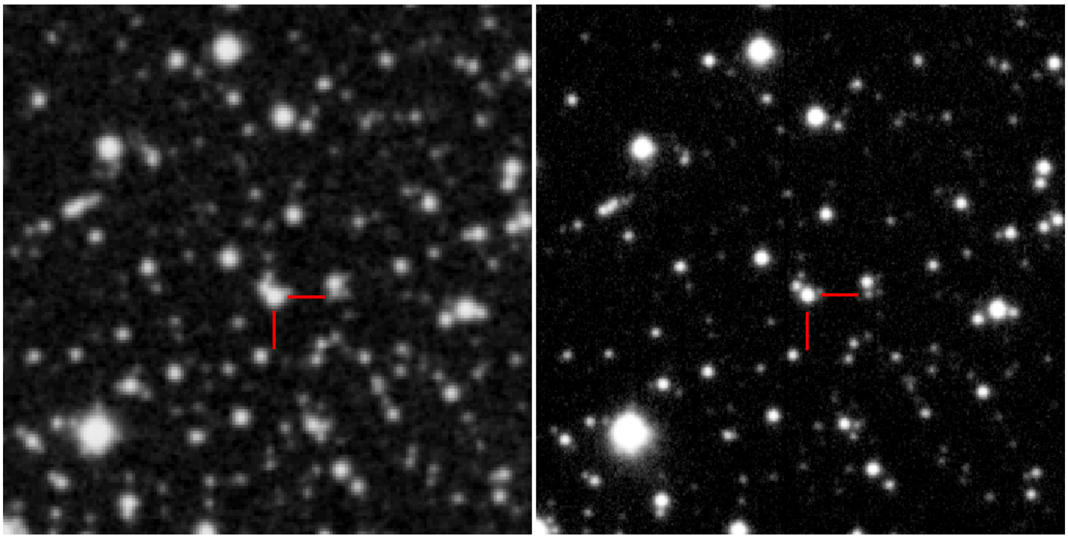

Figure 5. Left panel: Corresponding field from DSS2 Red survey, obviously capturing CzeV404 during outburst phase. Right panel: The same field imaged with the 0.65 m telescope of the Ondřejov Observatory. This image shows 4 stars within or close to the photometric aperture used to measure CzeV404. Sampling is $0.''5$/pixel.

Series start (JD)	Length [h]	Data points	Max. mag	Supposed state
2456095.4311	1:42	30	16.7	quiescence
2456101.4244	1:11	22	16.6	quiescence
2456121.3822	3:39	65	16.6	quiescence
2456131.3493	4:16	76	15.5	outburst
2456132.3568	3:49	67	16.4	quiescence
2456145.3486	1:18	24	14.4	superoutburst
2456152.3816	3:35	64	14.4	superoutburst
2456153.3428	2:27	44	14.5	superoutburst
2456155.3432	4:22	79	14.9	superoutburst
2456157.3776	3:08	56	15.1	superoutburst
2456158.3410	4:32	77	15.5	superoutburst
2456159.3311	4:40	80	16.2	quiescence
2456160.3266	1:59	36	16.3	quiescence
2456180.2841	4:42	81	15.6	outburst
2456181.3362	2:48	45	16.4	quiescence

Table 1. A summary of CzeV404 observations in 2012.

Note: Maximum magnitudes of each series were calculated as comparison star V magnitude (13.3 mag, derived from the USNO A-2.0 catalog) plus the instrumental magnitude of the data set in the Clear filter.

Supposed state was determined from the light curve on figure 1.

Minima during the quiescence phase often dropped below the minimal detectable brightness (around $V \sim 17$ mag, the actual limit slightly varies among individual datasets, because it depends on observing conditions like seeing, sky transparency, Moon phase etc.), thus they are missing from the data sets.

In addition to 15 observing nights in 2012, we acquired another 8 observations of the CzeV404 from July to August 2013. Unfortunately, the weather in 2013 did not allow to acquire data as frequent as needed and therefore the estimation of outburst length and possible distinguishing between outbursts and superoutbursts was not possible. However, we were able to identify 10 more eclipses in 2013, which significantly increased precision of determination of the orbital period.

Series start (JD)	Length [h]	Data points	Max. mag
2456483.3718	4:24	77	15.4
2456494.3551	5:04	89	15.1
2456495.3611	4:48	86	15.7
2456497.3687	4:33	75	16.1
2456507.3681	4:06	72	15.1
2456508.3395	3:58	71	15.8
2456519.3627	2:32	45	14.7
2456522.3395	3:54	53	15.6

Table 2. A summary of CzeV404 observations in 2013.

Results

There were 12 minima observed in 2012 and 11 more minima observed in 2013. Each minimum is very deep (~ 0.5 mag) and distinct. The orbital period is well constrained, because we observed two consecutive minima in five different nights.

We used the online tool[2] to fit light curves around each minimum with an empiric function (Brát, Pejcha, Mikulášek, 2014) and to determine the center of the eclipse together with uncertainties in 16 cases (see table 3).

BJD	σ (bootstrap)
2456145.38776	+0.00085/-0.00010
2456152.44554	+0.00072/-0.00035
2456155.38005	+0.00003/-0.00057
2456155.48286	+0.00018/-0.00022
2456157.44426	+0.00153/-0.00010
2456158.42416	+0.00010/-0.00013
2456483.46431	+0.00067/-0.00004
2456494.44191	+0.00119/-0.00004
2456494.54025	+0.00059/-0.00152
2456495.42247	+0.00124/-0.00016
2456495.52077	+0.00017/-0.00010
2456507.38021	+0.00099/-0.00011
2456507.47783	+0.00013/-0.00103
2456508.36069	+0.00077/-0.00036
2456519.43606	+0.00077/-0.00034
2456522.47506	+0.00011/-0.00039

Table 3. A summary of CzeV404 minima used to determine orbital period.

We used four cases, in which two subsequent eclipses occurred in single uninterrupted run, to estimate orbital period. This estimate was used to determine epoch of each

[2]http://var2.astro.cz

minimum and then we used linear regression to fit times of eclipses against epoch number to determine the precise period.

$$BJD_{\text{min}} = 2456145.3895(9) + 0.098021(1) \times \text{E}$$

Figure 6 shows observations from 2012 folded with the determined orbital period. It is worth noting that the period ~ 2.35 hours is within the "period gap" of cataclysmic variables.

Brightenings caused by the accretion disc hot spot, observable immediately before each eclipse during the quiescence and outburst phases, disappeared during the superoutburst phase from 12$^{\text{th}}$ August to 17$^{\text{th}}$ August, 2012. Instead, a clearly visible superhump appeared in the light curve.

We only slightly modified the method, used for determination of the orbital period, to determine the period of superhump maxima. We inverted the magnitude scale on particular nights, so the peaks appeared as minima, and utilized the same tool to fit light curves around each minimum with an empiric function (Brát, Pejcha, Mikulášek, 2014) and to determine the center of each peak together with uncertainties in 7 cases (see table 4).

We observed two subsequent maxima in single uninterrupted run in three cases. These three cases were used to estimate period of superhump brightening. This estimate was used to determine epoch of each maximum and then we used linear regression to fit times of peak brightness against the epoch number to determine the superhump period.

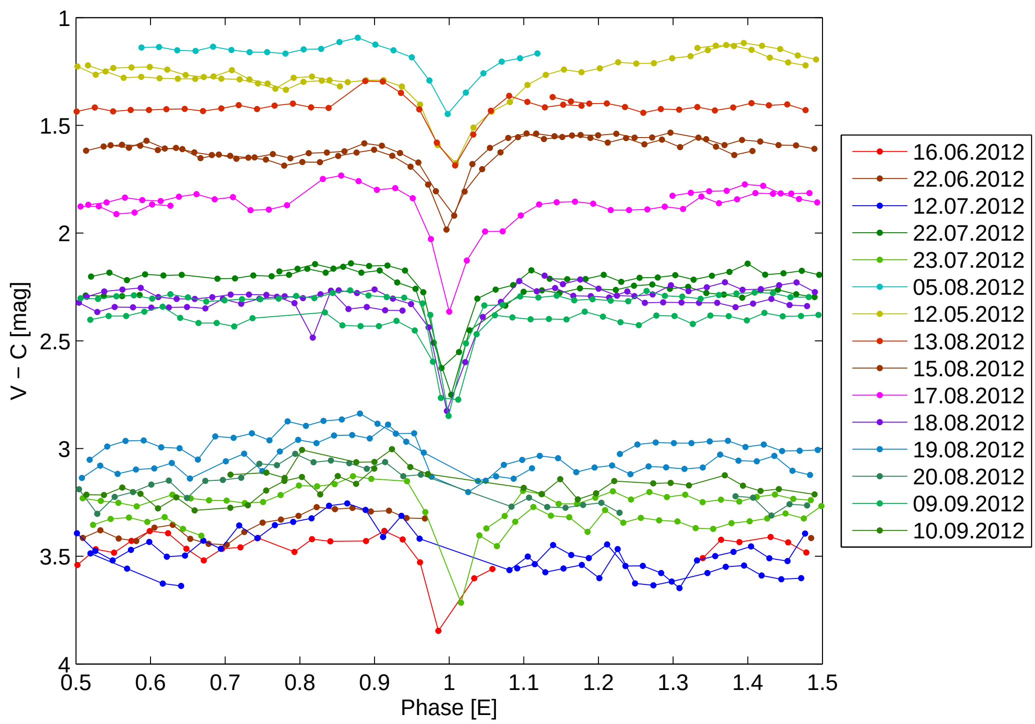

Figure 6. All CzeV404 observations folded with the 0.098021 days orbital period.

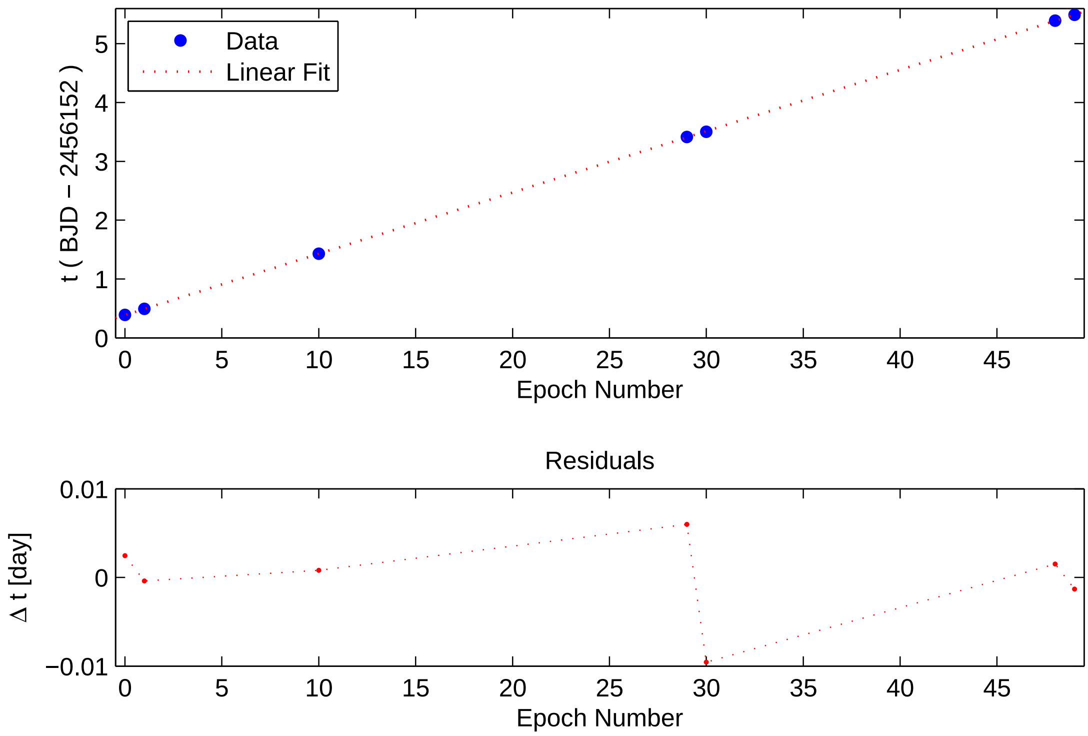

Figure 7. Fit of the Czev404 superhump period.

BJD	σ (bootstrap)
2456152.38888	+0.00064/-0.00119
2456152.49025	+0.00009/-0.00014
2456153.42948	+0.00023/-0.00036
2456155.41488	+0.00124/-0.00088
2456155.50354	+0.00131/-0.00099
2456157.39060	+0.00042/-0.00071
2456157.49200	+0.00106/-0.00133

Table 4. A summary of CzeV404 superhump maxima used to determine the superhump period.

With the exception of 13$^{\text{th}}$ August, 2012, stellar eclipses did not overlap with superhump maxima, so they did not affect measurements of the maxima instances. The superhump on 13$^{\text{th}}$ August 2012 occurred at the same time as the stellar eclipse, but lasted longer than the eclipse itself. We did not use the data points acquired during the eclipse and calculated the instant of the superhump maximum from the portions of light curve not affected by the eclipse. Resulting superhump period is:

$$BJD_{\text{max}} = 2456155.410(5) + 0.1042(1) \times \text{E}$$

Measurement of both orbital and superhump periods enables calculation of a period excess $\epsilon = P_{sh}/P_{orb} - 1$ (Stolz & Schoembs, 1984), where P_{sh} is the superhump period and P_{orb} is the orbital period.

$$\epsilon = 0.063 \pm 0.001$$

The determined period excess roughly corresponds to the empiric relation between the period excess and the orbital period, given by Olech et al. (2011). However, this relation predicts period excess around 0.05 for the orbital period ~0.1 days.

Patterson (1998) published an empiric relation between a CV period excess and a system mass ratio $q = M_2/M_1$:

$$\epsilon = \frac{0.23q}{1 + 0.27q}. \tag{1}$$

Resulting CzeV404 mass ratio is

$$q = 0.30 \pm 0.01.$$

However, according to Olech et al. (2011), that high mass ratio can cause significant problems for establishing regions in 3:1 resonance in the accretion disk, considered to be the source of superhump brightenings. Obviously CzeV404 deserves more observations to gather more data from subsequent superoutbursts, especially periods of superhumps.

Acknowledgments

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