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DISCOVERY OF AN SU UMa-TYPE ECLIPSING CATACLYSMIC VARIABLE STAR INSIDE THE CV “PERIOD GAP”

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Introduction

SU UMa-type cataclysmic variable (CV) stars consists of close pair of a white dwarf (primary) and a main sequence (secondary) star. The secondary star fills its Roche-lobe, which causes a mass transfer to the primary star, creating an accretion disc (provided 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).

The orbital periods of SU UMa-type CVs 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 the 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, $\alpha_{2000} = 18^{\mathrm{h}}30^{\mathrm{m}}1\overset{\mathrm{s}}{.}833$, $\delta_{2000} = +12^\circ33'47\overset{''}{.}43$) was found on a series of wide-field CCD exposures of a field in Hercules acquired on 22 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. 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

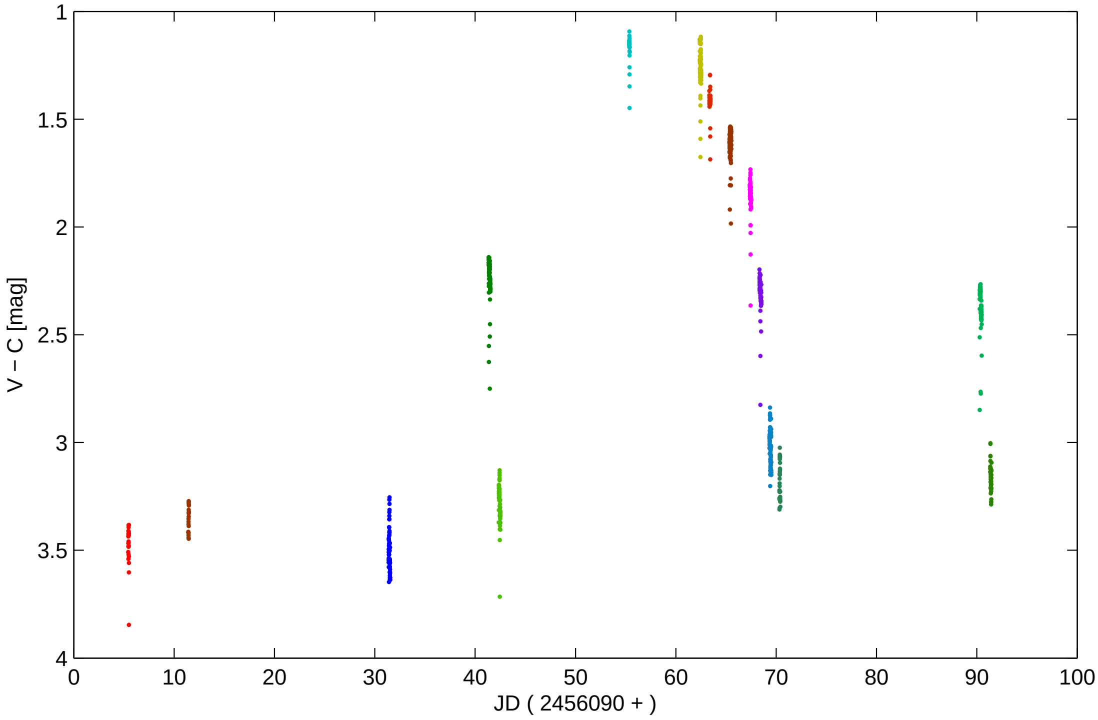

Figure 1. Observations of CzeV404 spanning June to September 2012.

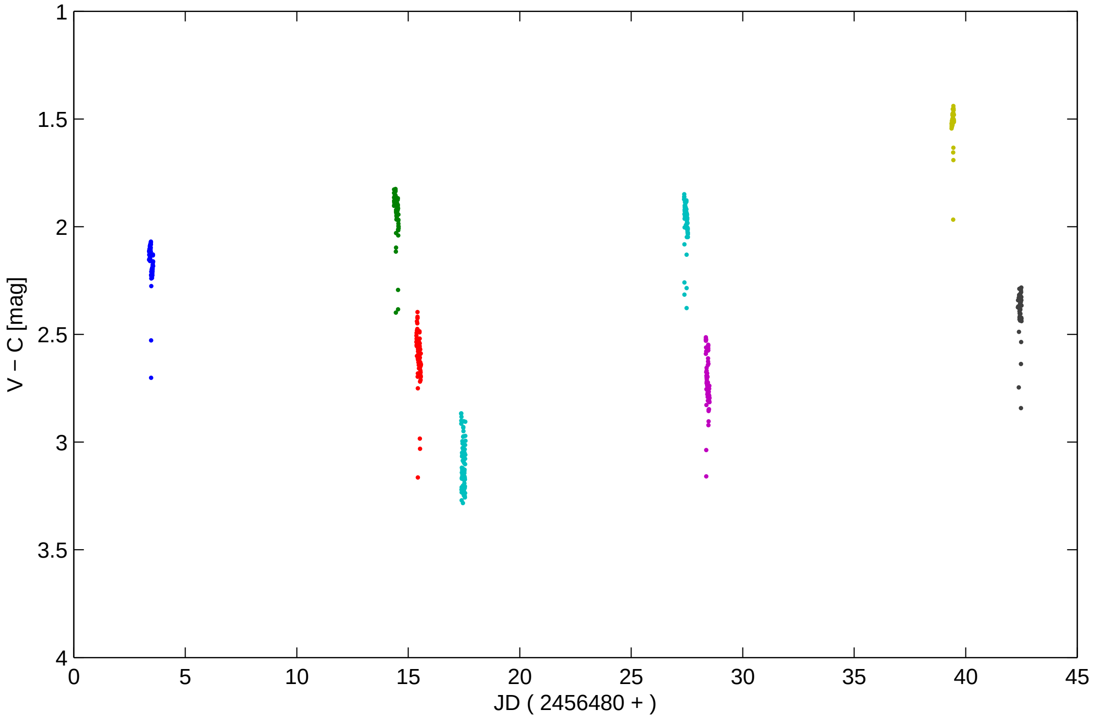

Figure 2. Observations of CzeV404 spanning June to August 2013.

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 $B - V$ indices 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 (Figures 1 and 2). We observed two types of outbursts: short ones lasting several 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).

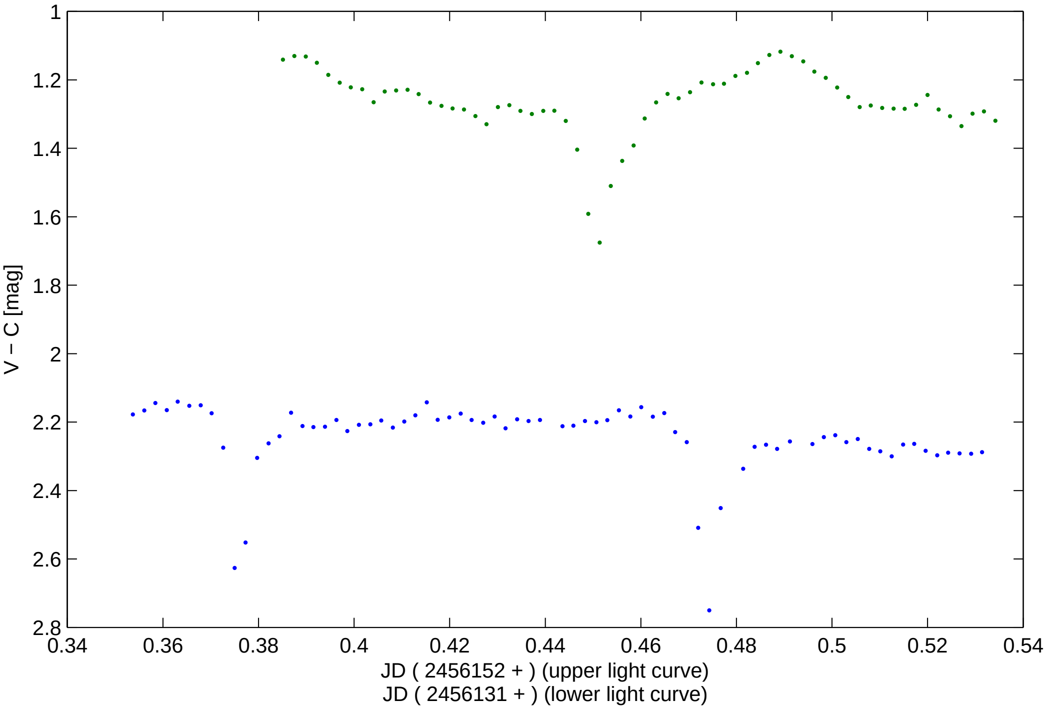

Figure 3. Light curves of CzeV404 during outburst on 22 July 2012 (lower light curve) and during superoutburst on 12 August 2012 (upper light curve).

In the outburst phase the CzeV404 light curve showed brightenings just before eclipse, caused by an accretion disc hot spot. This brightening disappeared during superoutburst phase, but we observed periodic oscillations with a period close to but not identical with 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 photometric measurements are affected by a nearby star, just around 3.6 pixels (∼ 5 arc seconds) apart (see the left panel in Figures 4 and 5). The brightness of the nearby star was not measured due to close proximity of both stars, but it is somewhat fainter 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 high-resolution image acquired with the 0.65 m telescope of the Ondřejov Observatory (Astronomical Institute of the Czech Academy of Sciences) with $0\overset{\prime\prime}{.}5$/pixel sampling show three faint stars in close angular proximity to CzeC404 (see the right panel in Figure 5). However, the faint star to the north of CzeV404 is outside of the photometric aperture and while the faint star to the west of 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.

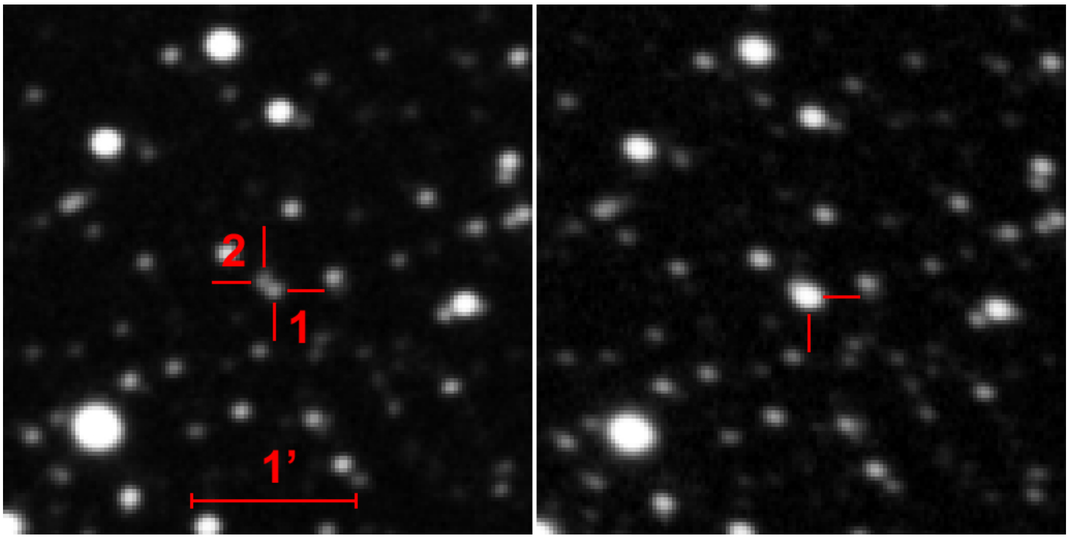

Figure 4. Left panel: CzeV404 (1) in quiescence state and a nearby star approx. 5″ apart to the north-east (2) on 12 July 2012. Right panel: The same field with CzeV404 captured during superoutburst on 5 August 2012. Star shapes are slightly distorted due to aberrations of used wide-field optics. Both panels are cropped from the original photometry telescope field of view, the image scale is $1\overset{\prime\prime}{.}39$/pixel.

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

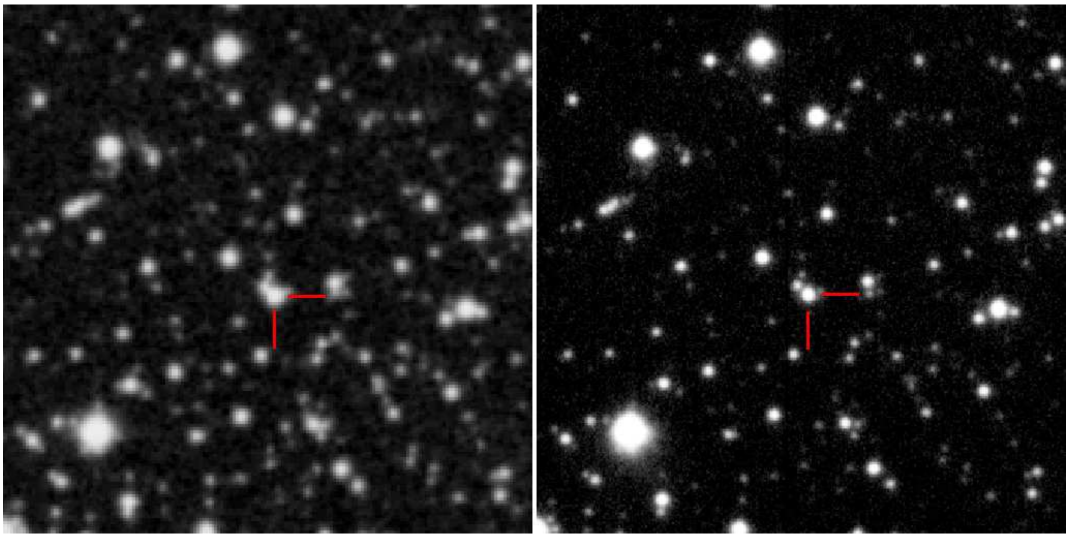

Figure 5. Left panel: Corresponding field from DSS2 Red survey, obviously capturing CzeV404 during an outburst phase. Right panel: The same field imaged with the 0.65 m telescope of the Ondřejov Observatory. This image shows 4 stars within or close to the photometric aperture used to measure CzeV404. 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 in 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, lunar phase etc.), thus they are missing from the data sets.

In addition to 15 observing nights in 2012, we acquired another 8 observations of 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 distinction 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 ($\sim$ 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 empirical 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

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[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.

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

Figure 6 shows observations from 2012 folded with the determined orbital period. It is worth noting that the period $\sim$ 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 August to 17 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 empirical 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.

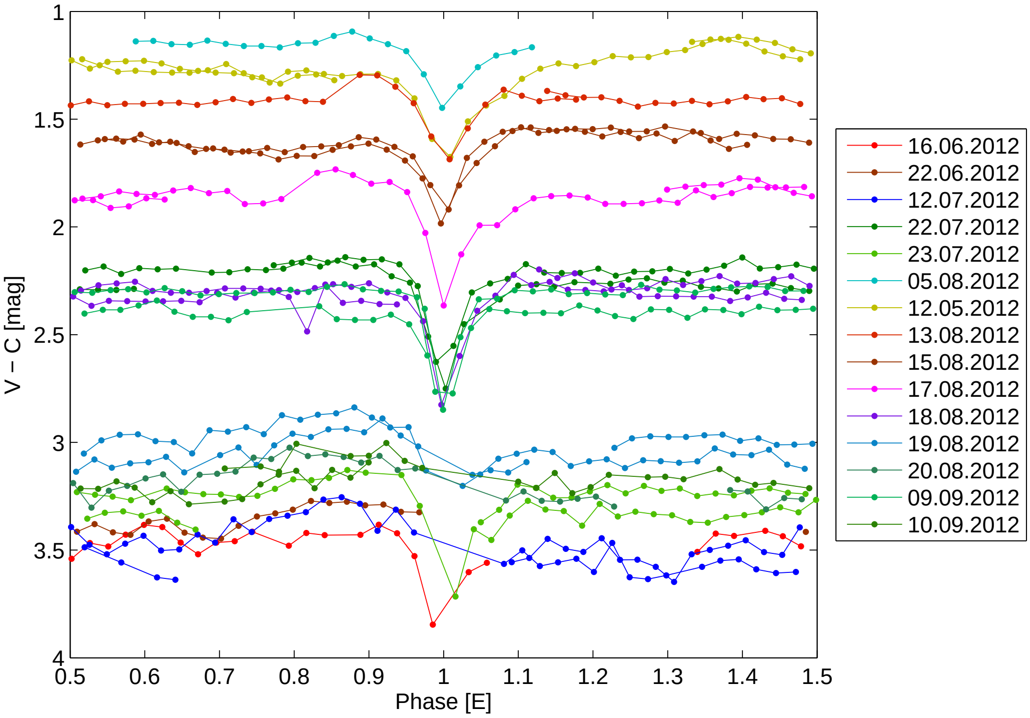

Figure 6. All CzeV404 observations folded with the 0.098021 days orbital period.

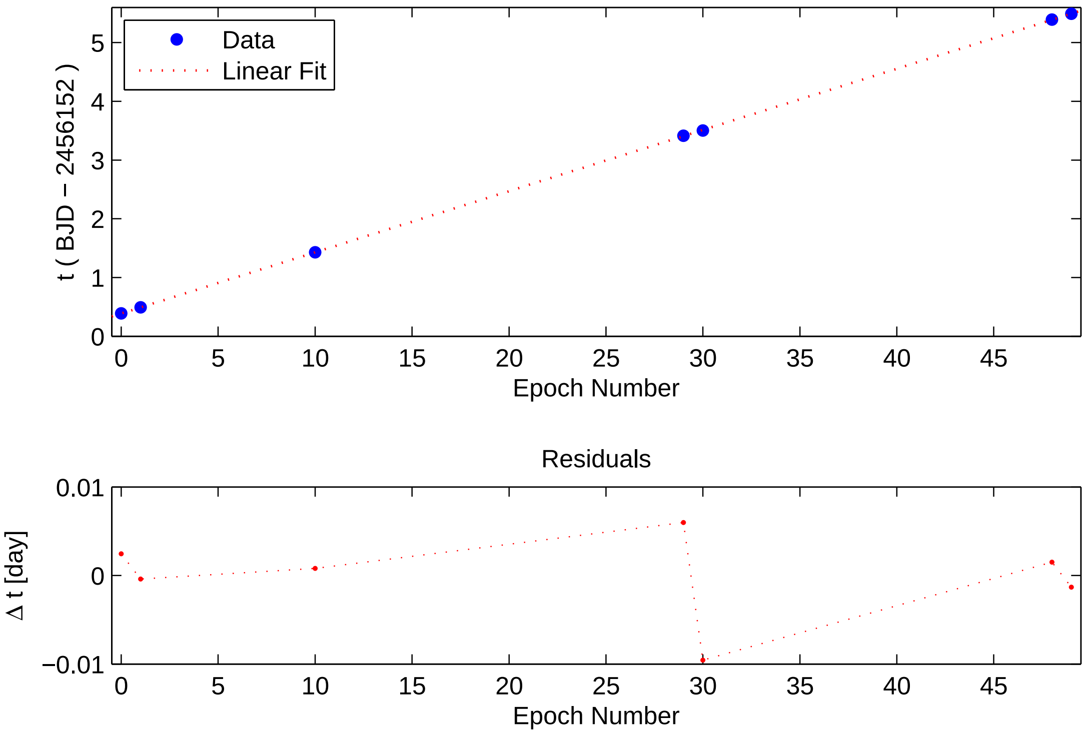

Figure 7. Fit of the CzeV404 superhump period.

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 on 13 August 2012, stellar eclipses did not overlap with superhump maxima, so they did not affect measurements of the maxima instances. The superhump on 13 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. The resulting superhump period is:

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

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

$$\epsilon = 0.063 \pm 0.001$$

The determined period excess roughly corresponds to the empirical 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 empirical relation between a CV period excess and a system mass ratio $q = M_2/M_1$:

$$\epsilon = \frac{0.23q}{1 + 0.27q}. \qquad (1)$$

The resulting mass ratio of CzeV404 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.

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