Dwarf Nova V1040 Centauri and Variable Stars in its Vicinity

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ABSTRACT

We present the results of a photometric campaign of the dwarf nova V1040 Cen. The light curve shows two normal outbursts with recurrence time $\approx 40$ days and amplitude $\approx 2.5$ mag. Quiescence data show oscillations with periods in the range $\approx 0.1$ days (2.4 h) to $\approx 0.5$ days (12 h) of unknown origin. We measured the orbital period of V1040 Cen to be $P_{\text{orb}} = 0.060458(80)$ days (1.451 $\pm$ 0.002 h). Based on the $M_v - P_{\text{orb}}$ relation we found the distance of V1040 Cen to be $137 \pm 31$ pc. In this paper we also report the detection of eleven new variable stars in the field of the monitored dwarf nova.

Key words: accretion, accretion discs - binaries: cataclysmic variables, stars: dwarfnovae, oscillations, stars: individual: V1040 Cen, RX J1155.4-5641, AAVSO 1150-56, 2MASS J11552726-5641561

1. Introduction

Cataclysmic variables (CVs) are interacting binaries containing a main-sequence or slightly evolved secondary star losing mass via Roche lobe overflow onto a white dwarf primary (Warner 1995). In binaries with a weak magnetic field ($B < 10^5$ G) an accretion disc is formed around the primary. Today it is clear that the accretion disc thermal instability is the cause of repetitive outbursts observed in some CVs called dwarf novae (DNe) - see Osaki (1996) for a review.

Dwarf novae present a huge variety of light curve behavior. In this paper we continue our studies devoted to those stars (e.g., Olech et al. 2009, Rutkowski et al. ...)
V1040 Cen is a DN with the orbital period of $P_{\text{orb}} \approx 0.060416$ days (1.45 h) (Longa-Pena 2009). The distance to this object is uncertain and is estimated to be 492 pc by Ak et al. (2008), while Pretorius and Knigge (2008b) gives a lower limit distance to this object as 40 pc. Superoutburst light curves were previously studied by Patterson et al. (2003) leading to the discovery of superhumps with a period of $P_{\text{orb}} = 0.06028(10)$ days ($\approx 1.45$ h). Using high-speed photometry Woudt and Warner (2010) studied Quasi Periodic Oscillations (QPOs) and Dwarf Nova Oscillations (DNOs) in this object. Kato et al. (2003) on the basis of VSNET data estimated the superoutburst cycle to be $\approx 211$ d. Our observations and its analysis are presented in Sections 2, 3 and 4.

Research devoted to a particular problem also often brings some by-products in the form of additional discoveries. V1040 Cen is located close to the Galactic plane in a relatively crowded area. We used this opportunity to check how the brightness changes for other stars present in our frames. Careful analysis allowed us to discover eleven new variable stars which we describe in detail in Section 6.

2. Observations and Data Reductions

We observed V1040 Cen using three telescopes at three different locations: for 4 nights in March 2009 with the 1.0-m Elizabeth Telescope at the South African Astronomical Observatory (SAAO), for 31 nights in March-May 2009 with the 1.3-m Warsaw telescope at Las Campanas Observatory (LCO), and for 14 nights in April 2009 with the SMARTS 0.9-m telescope at Cerro Tololo Inter-American Observatory (CTIO). Table 1 gives details.

The richest observation set comes from CTIO where we obtained 2020 frames in "white light" using one $1024 \times 1024$ quartile of the 2K $\times$ 2K optical imager at a scale of $0.396$/pixel. The exposure times ranged from 30 s to 90 s. Occasionally we took images in $B$, $V$, and $I$ filters with exposure times of 300 s, 240 s and 240 s, respectively.

The data from LCO was taken mostly during the twilight using a $1024 \times 2048$ subraster of an eight SITE 2048 $\times$ 4096 CCD mosaic camera at a scale of $0.26$/pixel. Only $V$-band images with exposure times between 30 s and 90 s were collected.

The SAAO data were collected using back-illuminated CCD camera "STE3" of a size of $512 \times 512$ pixels equipped with liquid nitrogen cooling. Observations were taken in "white light" with exposure times of an order of one minute.

All images were de-biased and flat-fielded using the IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the} package. The pho-
Table 1: Journal of photometric observations of V1040 Cen

| Site         | Observing period | Filter | Number of frames |
|--------------|------------------|--------|------------------|
| SAAO (1.0 m) | 2009 Mar 15 - Mar 18 | -      | 127              |
| LCO (1.3 m)  | 2009 Mar 24 - May 3 | V      | 122              |
| CTIO (0.9 m) | 2009 Apr 2 -15    |        | 2020             |
|              |                   | B      | 6                |
|              |                   | V      | 6                |
|              |                   | I      | 6                |

Photometry from the CTIO data was extracted with the help of the Difference Image Analysis Package (DIAPL) written by Woźniak (2000) and recently modified by W. Pych. The package is an implementation of the method developed by Alard and Lupton (1998). A reference frame was constructed by combining 13 individual images taken on the night of 2009 April 14/15. Profile photometry for the reference frame was extracted with DAOPHOT/ALLSTAR (Stetson 1987). These measurements were used to transform the light curves from differential flux units into instrumental magnitudes. For the LCO and SAAO data we decided to extract only aperture photometry with DAOPHOT.

The CTIO images were also used to search for variable stars. We inspected directly by eye the light curves of 711 stars in a 6'2 x 6'2 field roughly centered on V1040 Cen. For completeness we performed an independent period search with the TATRY code (Schwarzenberg-Czerny 1996).

3. Global light curve

Figure 1 presents the overall light curve from our three-months observational campaign. Since the filter transmission for the R pass-band is very close to observations made in “white light” we label the y-axis of the plot accordingly by ≈ R magnitude. Three types of symbols indicate data obtained with different telescopes. In this figure one can easily notice three episodes of significant brightenings. At least two of them (close to HJD ≈ 2454906 and HJD ≈ 2454946) could be considered as normal dwarf nova outbursts. Time intervals between consecutive eruptions are ≈ 9 d and ≈ 31 d. Assuming that the second brightening (around HJD=2454912.5) is just fluctuation, the period between two detected consecutive outbursts is ≈ 40 d. This value is only slightly different than ≈ 35 d period mentioned by Woudt and Warner (2010). However, taking into account the low level amplitude of the first two brightenings and the small number of points during their peaks we should not draw too far-reaching conclusions about this period. On the other hand it is also known that outburst events in CVs are not strictly periodic so most likely this is just...
an effect of this property.

The $R$ magnitude has been derived as the difference between the variable and the comparison stars designated by numbers 124, 129 and 141 on the AAVSO chart. Due to incompatibility of the photometric systems the zero-point errors can likely be as big as 0.2 mag.

![Graph](image-url)

**Fig. 1.** Complete light curve of V1040 Cen. Dots, open circles and open squares represent data gathered using SMARTS(CTIO), LCO and SAAO telescopes respectively. The inset presents $BV$ measurements obtained using the SMART telescope. The y-axis of the inset was vertically shifted in order to improve the readability of the graph. The x-axis scale is the same for the inset and the rest of the figure.

During SMART telescope observations we made occasionally $BVI$ measurements of V1040 Cen. The obtained $BVI$ magnitudes are presented as an inset in Figure 1. These magnitudes were obtained using comparison stars from AAVSO Variable Star Database and Aladin sky atlas. Errors come mostly from these transformations. One can clearly see that $V$ and $I$ magnitudes resemble the LCO light curve. However the $B$ magnitudes gradually decreases which can be a manifestation of disc cooling after last outburst. The amplitude of the observed outbursts reaches 2.5 mag. The duration of the eruptions and other properties mentioned above strongly suggest, that those were normal dwarf nova outbursts.
Fig. 2. Example of light curve variations of V1040 Cen obtained with the 0.9-m SMARTS telescopes. Times of the extrema calculated using the ephemeris (1) and (2) are also presented. Solid vertical lines indicate timings of the light curve minima corresponding to ephemeris (1) while dashed vertical lines show timings of the minima corresponding to ephemeris (2). Only the epoch number of ephemeris (1) is shown for clarity.

4. Power spectrum

The data, which span the longest time, were obtained with 1.3-m LCO telescope. They have, however, quite poor sampling which is not suitable to draw conclusions about variations within timescales of hours. This opportunity is given by SAAO and SMARTS data. Figure 2 presents examples of light curve variations obtained by the SMARTS telescope. The most prominent variations which can be noticed have a roughly constant amplitude of $\approx 0.8$ mag.
In addition, careful inspection allows us to notice the smaller amplitude light variations with an amplitude up to $\approx 0.35$ mag superimposed on the main light curve. We use the Fourier transform to reveal all different frequencies that constitute it.

The SAAO and SMARTS telescopes data were used for this analysis. The procedure which we used involves trend removing. Two approaches were applied. For each night separately we fitted a first or second order polynomial and subtracted it from the original data. This resulted in subtracting the most visible $\approx 0.8$ mag amplitude variations from the light curve. Such detrended light curve was analyzed by the ZUZA - Time Series Analysis code (Schwarzenberg-Czerny 1996). The resulting periodogram is shown in Figure 3. The highest peak at a frequency $f_{\text{orb}} = (16.538 \pm 0.026)$ c/d corresponds to an orbital period $P_{\text{orb}} = 0.060458(80)$ days $= (1.451 \pm 0.002)$ h. The spectroscopically determined period $(1.45176 \pm 0.00002)$ h by Longa-Pena (2009) falls within this error range. The second highest peak apart from the daily aliases of $f_{\text{orb}}$ is $33.1$ c/d $\approx 2f_{\text{orb}}$ which we interpret as harmonic frequency.

As it was mentioned before the most prominent brightness changes have an amplitude of $\approx 0.8$ mag, however this modulation has been removed during detrending procedure. Thus we had to repeat the detrending procedure on the raw data, but

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3http://www.noao.edu/meetings/wildstars2/posters/monday/p-longa-poster.png
this time we fit to consecutive nights only first order polynomial. This brought all the curves to the same level without removing considered modulations. Next we applied a prewhitening procedure to remove the orbital frequency $f_{\text{orb}} = 16.538$ c/d and its first harmonics from the data. The resulting periodogram is presented in Figure 4. One can see that all statistically significant information is present below $f = 12$ c/d. Two clear peaks can be noticed – namely $f_1 = 5.35$ c/d and $f_2 = 9.31$ c/d. After investigation of the periodogram one can notice that the remaining variations are not strictly periodic – there are several minor peaks spread around the frequencies $f_1$ and $f_2$ within the range $\pm \approx 2$ c/d.

![Figure 4](https://example.com/fig4.png)

In order to check if the detected oscillation period varies randomly or rather shows systematic lengthening or shortening we performed an $O-C$ analysis. To construct it we used the periods corresponding to frequencies $f_1$ and $f_2$. Since in most cases minima are much sharper and better visible we used them for this analysis. The results, however, are inconclusive and difficult to interpret. There is no noticeable tendency in obtained $O-C$ diagram. For better visualization of this behavior we put vertical markers corresponding to the timings of minima in the Fig. 2. The markers locations were calculated based on the following ephemeris:

$$E_{1_{\text{min}}} = 26.14(1) + 0.1863(2) \cdot E$$  \hspace{1cm} (1)

for the dashed lines, and
\[ E_{2_{\text{min}}} = 26.1138(52) + 0^{d}.10750(7) \cdot E \]  

for the solid lines. The resulting light curves are shown in Fig 5.

At least in the case of two other objects (i.e., SDSS J162520.29 - Olech et al. 2011, and 1RXS J053234.9 - Rutkowski et al. 2010) the similar low frequency signals below \( \approx 10 \) c/d were also observed. So far their nature is unknown. The presence of this kind of low frequency oscillations (for dwarf novae inside or below the period gap) is puzzling.
One can speculate that explanation of this low frequency signals can involve oscillations of the hot spot and/or reflect the long-term variation of the mass transfer rate.

5. Distance to V1040 Cen

So far, there are two estimates of the distance of V1040 Cen. Pretorius and Knigge (2008b) estimated a lower limit of 40 pc for the distance to the system. Their distance determination method was based on infrared magnitudes that are calculated from theoretical models of the secondary stars and orbital periods by Knigge (2006) (see also, Pretorius and Knigge, 2008a). They assumed that the secondary stars fill their Roche lobe. However, Ak et al.’s (2007, 2008) period-luminosity-colour (PLC) relation gives a value of 492 pc for the lower limit of distance to V1040 Cen.

The difference between two estimates of distance to V1040 Cen comes from the absolute magnitudes calculated by Ak et al. (2008) and Knigge (2006). Ak et al. (2008) found the system’s absolute brightness in JHK_s photometric bands as twice the theoretical JHK_s absolute brightness found by Knigge (2006).

A different approach is to use the outburst maximum brightness in the V band. This procedure is based on the assumption that the accretion disc maximum brightness during outburst of a dwarf nova is a good standard candle. Based on the relation given by Warner (1995, eq 3.4):

\[ M_v(\text{max}) = 5.74 - 0.259P_{\text{orb}}[\text{h}] \]  

(3)

Using \( P_{\text{orb}} = 1.45 \) h, for V1040 Cen we obtain \( M_v = (5.36 \pm 0.2) \) mag. The brightness of V1040 Cen during the observed outburst maximum was measured to be \( (11.48 \pm 0.2) \) mag. Based on Schlegel, Finkbeiner & Davis (1998) extinction maps at NASA/IPAC Infrared Science Archive[^4] for the position of V1040 Cen we obtain an extinction \( A_v = 1.38 \) mag. Using the above numbers we were able to estimate the distance to V1040 Cen to be \( d = (88 \pm 31) \) pc, where the error was calculated based on exact differential and corresponds to 1 sigma. This means that the 40 pc of Pretorius & Knigge (2008b) - which additionally is a lower limit - is well within 2 sigmas of our value. Moreover, one can notice that this 40 pc value was based on the semi-empirical donor sequence. So, one might expect these lower limits presented in their work are typically underestimated true distances by about a factor of 2. Therefore distance estimation of Pretorius & Knigge (2008b) of V1040 Cen would actually be around 80 pc, which is in excellent agreement with our 88 \pm 31 pc estimate.

On the other hand, value of 492 pc obtained by Ak et al. (2008) significantly disagree with our result. But one should keep in mind that the Schlegel’s \( A_v \) absorption value, is the total absorption from us to the edge of the Galaxy - therefore the

[^4]: [http://irsa.ipac.caltech.edu/applications/DUST/](http://irsa.ipac.caltech.edu/applications/DUST/)
Table 2: Basic data on detected variables in the field of V1040 Cen.

| Var | RA(2000.0) | Dec(2000.0) | \( R_{\text{max}} \) | \( A_R \) | \( P \) | Type |
|-----|------------|-------------|-----------------|--------|-------|------|
| V1  | 11:55:06.34 | -56:43:30.1 | 15.67 | 0.02 | 7.5(5) | puls? |
| V2  | 11:55:06.79 | -56:42:12.8 | 14.98 | 0.04 | 4.1215(5) | EW |
| V3  | 11:55:08.43 | -56:40:35.5 | 16.84 | 0.64 | 0.41215(5) | EW |
| V4  | 11:55:10.57 | -56:40:49.6 | 17.37 | 0.11 | 0.41215(5) | EW |
| V5  | 11:55:18.50 | -56:40:07.2 | 17.50 | 0.03 | | per? |
| V6  | 11:55:21.74 | -56:42:29.0 | 19.65 | 0.80 | 0.5859(1) | EA |
| V7  | 11:55:24.97 | -56:39:18.7 | 14.80 | 0.03 | 9.1(1) | puls? |
| V8  | 11:55:26.77 | -56:42:26.7 | 16.11 | 0.06 | 8.9(1) | puls? |
| V9  | 11:55:42.86 | -56:41:35.1 | 17.13 | 0.50 | 0.7137(1) | EB |
| V10 | 11:55:45.77 | -56:41:23.8 | 18.95 | 0.25 | 2.510(1) | EA |
| V11 | 11:55:46.93 | -56:41:09.4 | 15.62 | 0.04 | 1.27(1) | ecl? |

Absorption for V1040 Cen might be lower. If we take \( E(B−V) = 0.139 \) mag from Ak et al. (2008) then we obtain \( A_v = 0.431 \) mag. Consequently, a new distance estimate is about \( 137 \pm 31 \text{ pc} \). This new corrected distance value, however, still remain in disagreement with \( 492 \text{ pc} \) given by Ak et al. (2008) but is well within 2 sigmas with dubled lower limit estimations (\( \approx 80 \text{ pc} \)) of Pretorius & Knigge (2008b). However, we believe that \( A_v \) inferred from Ak et al. (2008) is correct and, therefore we take \( d = 137 \pm 31 \text{ pc} \) as the most likely value.

In addition if main source of the errors comes from inaccurate determination of the outburst maximum, then, to achieve agreement with Ak et al. (2008) \( m_v \) must be different by at least \( \approx 2 \text{ mag} \) which seems unlikely. However one should take into account that the accretion disk brightness depends strongly on the viewing angle. Paczyński and Schwarzenberg-Czerny (1980) analysed this effect and presented a formula which shows that equation (3) works fine only for intermediate (\( \approx 57^\circ \)) system inclinations. Therefore, the disk will be \( \approx 1 \text{ mag} \) brighter for face-on systems or \( \approx 1.7 \text{ mag} \) faither for close to edge-on systems.

6. Variable stars in the field of V1040 Cen

V1040 Cen is located 5.3 deg from the Galactic plane in a relatively crowded area. The 14-day-long observations at CTIO allowed us to search for variable objects in the vicinity of the monitored dwarf nova. Within the 6'2 \times 6'2 field we found eleven new variables with brightness between 14.80 and 19.65 mag in the \( R \) band. In Table 2 we give information on equatorial coordinates, brightness, possible period and type of each variable. In Figs. 6 and 7 we present light curves and finding charts, respectively.

Four of the objects, V3, V6, V9, and V10, are bona fide eclipsing systems. We note that the orbital period of V10 can be twice longer than the given value of 2.510 d. The variable V3 is a W UMa-type binary star showing flat minima of the
same depth of 0.64 mag.

The nature of the other seven objects is not clear. Only for V1, V7, V8, and V11 we were able to derive periods. Long-period variables, namely V1, V7, and V8, are probably pulsating stars, while V11 seems to be an eclipsing binary. More observations are needed to definitively answer the question what type of objects they are.

7. Conclusions

a) We have presented the results of the observational campaign of the V1040 Cen. Light curve shows at least two normal outbursts. The $\approx 40$ days gap between them fits well with recurrence time period estimated by Woudt & Warner (2010). $\approx 40$ days and amplitude reaching 2.5 mag.
b) The quiescence data show oscillations with the period range from \( \approx 2.4h \) to \( \approx 4.8h \) which cannot be easily linked to any known phenomenon.

c) We have found the orbital period of V1040 Cyg to be \( P_{\text{orb}} = 0.060458(80) \) days \( (1.451 \pm 0.002 \text{ h}) \), which is also in excellent agreement with the orbital period determined from spectroscopy.

d) We estimated the distance to V1040 Cen to be \( (137 \pm 31) \) pc.

e) We detected eleven new variables in the field of V1040 Cen. Four of them are eclipsing binaries.

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