FOUR NEW VARIABLE STARS NEAR CL AURIGAE. II

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ABSTRACT. We report on a discovery of four new variable stars (USNO-B1.0 1234-0103195, 1235-0097170, 1236-0100293 and 1236-0100092) in the field of CL Aur. The stars are classified as eclipsing binary stars with orbital periods of 0.5137413(23) (EW type), 0.8698365(26) (EA) and 4.0055842(40) (EA with a significant orbital eccentricity), respectively. The fourth star (USNO-B1.0 1236-0100092) showed only one partial ascending branch of the light curves, although 22 nights were covered at the 61-cm telescope at the Sobaeksan Optical Astronomy Observatory (SOAO) in Korea. Fourteen minima timings for these stars are published separately. In an addition to the original discovery paper (Kim et al. 2010), we discuss methodological problems and present results of mathematical modeling of the light curves using other methods, i.e. trigonometric polynomial fits and the newly developed fit "NAV" ("New Algol Variable").

Key words: Variable stars: eclipsing: EA, EW -type; Data analysis: "NAV" algorithm.

During a study of the eclipsing binary CL Aur, we have discovered four new variable stars. The observations were made on 22 nights from 2003 November to 2005 February. The CCD camera has 2048×2048 pixels and an FOV of about $20'.5 \times 20'.5$, The filter set is attached to the 61 cm reflector at Sobaeksan Optical Astronomy Observatory (SOAO) in Korea. The exposure times were 75∼140 s for B, 45∼85 s for V, 33∼65 s for R, and 30∼60 s for I, respectively. A 2×2 binning mode was used. The nearby stars GSC 2393-1424 and GSC 2393-1418, imaged on the chip at the same time as the variable, were chosen as comparison and check stars, respectively. The co-ordinates (2000.0) of the comparison are $05^h13^m27^s.48$, +33°26'46.3". Unfortunately, there is no multicolor calibration for the comparison star, so the photometry is in differences "var-comp". The discovery paper was published by Kim et al. (2010). The star USNO-B1.0 1236-0100092 is an EA-type star with $T_0 = 2453412.0000(5)$ and $P_{orb} = 4.^d0055842(40)$. Here in brackets are the error estimates in units of last decimal digit. The secondary minimum is not covered completely by observations, but significantly shifted from the phase 0.5, indicating an elliptic orbit. USNO-B1.0 1234-0103195 shows only one ascending branch typical for EA-type stars, but, for determination of elements, new observatins are needed.

USNO B1.0 1236-0100293: EW -type

The object is a EW-type binary system. For analysis, we used an trigonometric polynomial (TP) fit $m_s(t)$ of order s:

$$m_s(t) = C_{s,1} + \sum_{j=1}^{s}(C_{s,2j}\cdot\cos(j\omega t) + C_{s,2j+1}\cdot\sin(j\omega t)),$$

where $\omega = 2\pi f$, $f = 1/P$ is trial frequency. The test function is defined as

$$S(f) = \frac{\sigma^2_{O-C,s}}{\sigma^2_{O-C,0}}, \quad \sigma^2_{O-C,s} = \sum_{k=1}^{N}(m_k - m_s(t_k))^2,$$

where $\sigma^2_{O-C,s}$ is variance of deviation of observational points from the $s-th$ order fit. The value $S(f)$ is a square of the correlation coefficient between the observed and calculated (for a given f) values. Detailed discussion of statistical properties of this test function, coefficients was presented by Andronov (1994, 2003). For the periodogram analysis, we have used the computer program "Multi-Column View" (MCV) described by Andronov and Baklanov (2004).

The periodogram (dependence of the test function $S(f)$ on trial frequency is shown in Fig. 1. Taking into account the EW type of variability, the first approach is TP fit with $s = 2$, which corresponds to a double wave and different depth of minima and (in a case of O'Connel effect). Thus the most prominent peak at the periodogram occurs at the orbital period P_{orb}, and the second one (in height) at a double frequency (half-period).

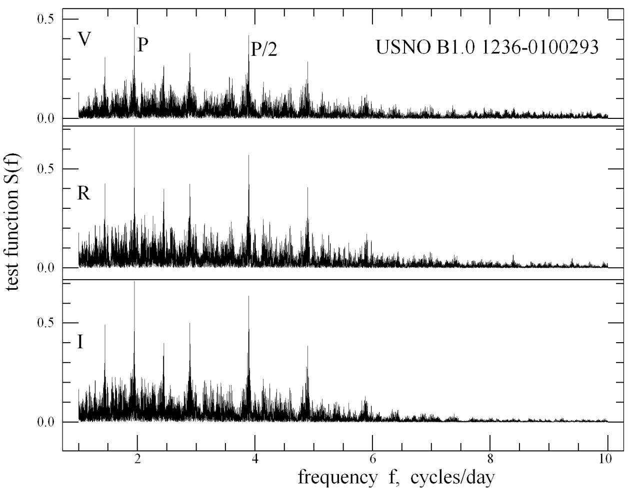

Figure 1: Periodogram of VRI observations (from top to bottom) of USNO B1.0 1236-0100293 computed using the 2-nd order trigonometric polynomial fit

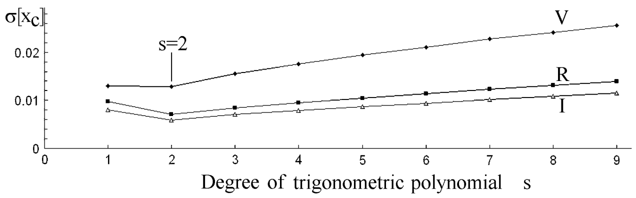

Figure 2: Dependence of the r.m.s. error estimate of the smoothing curve on the degree s of trigonometric polynomial for filters VRI.

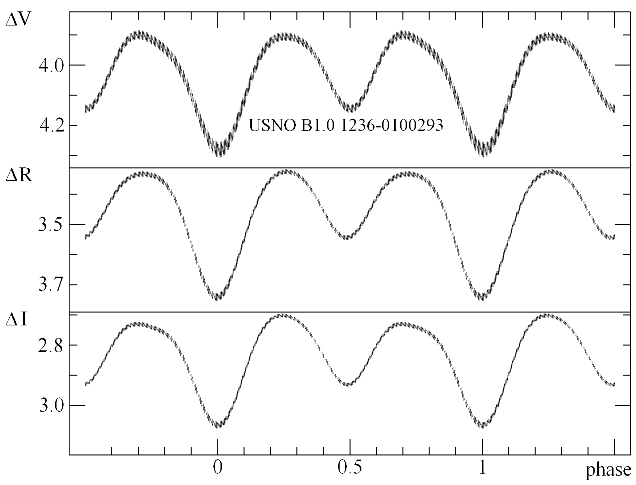

Figure 3: 4-nd order trigonometric polynomial fit to the VRI observations of USNO B1.0 1236-0100293. The thickness of the line corresponds to the "1σ" corridor. The ephemeris for the primary minimum is Min.HJD$= 2453215.5773 + 0.5137405 \cdot E$.

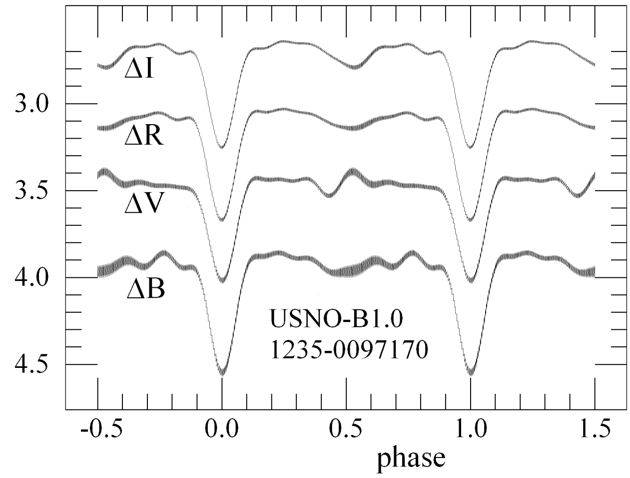

Figure 4: Trigonometric polynomial fits of 7-th order for BVRI observations of USNO-B1.0 1235-0097170 with "1σ" corridor.

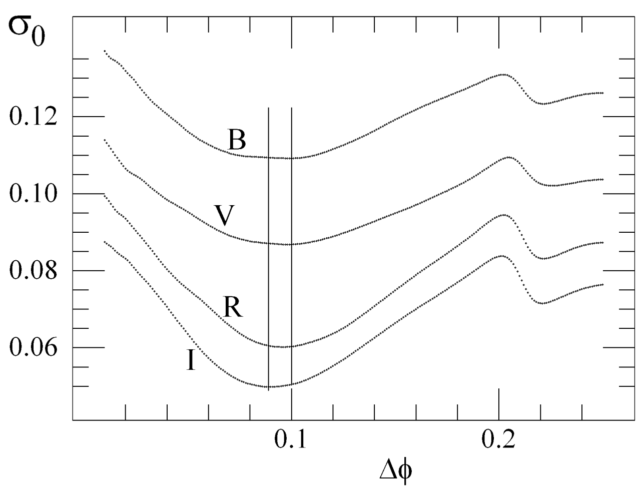

Figure 5: Dependence of the "unit weight error" on the eclipse half-width $\Delta\phi$ for filters BVRI.

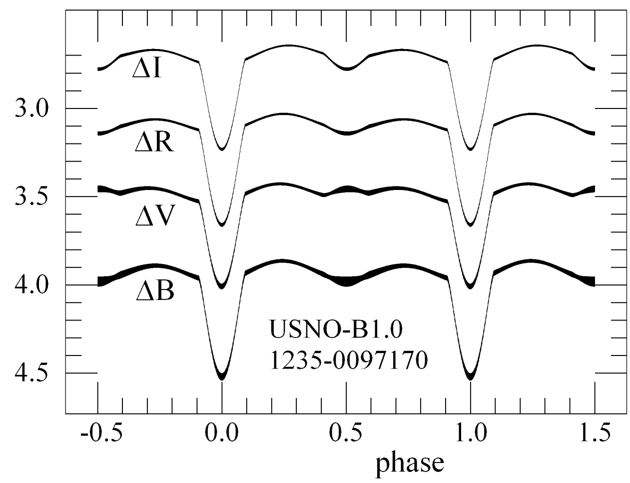

Figure 6: "NAV" fits to the BVRI observations of USNO-B1.0 1235-0097170 with "1σ" corridor. The ephemeris for the primary minimum is Min.HJD$=$ $2453208.8503 + 0.8698365 \cdot E$.

Due to statistical errors and non-orthogonality of the basic functions, the best fit values of the period and coefficients ($C_{s,i}$ are generally dependent on s even for the same i. Kim et al. (2010) used the method of Scargle (1982) with a least squares approximation

$$m_c(t) = \bar{m} + C_{s,2} \cdot \cos(\omega t) + C_{s,3} \cdot \sin(\omega t),$$

with $C_{s,1} = \bar{m}$ (sample mean of the observations) instead of a least square solution in TP-1. Moreover, the estimates of period and other coefficients are dependent on the photometric system. For the TP-2 fit, we obtained for VRI the period estimates of $0.^{\rm d}5137397(68)$, $0.^{\rm d}5137347(36)$, $0.^{\rm d}5137469(32)$. The weighted mean value is $P_{orb} = 0.^{\rm d}5137413(23)$, is slightly different from that of $0.^{\rm d}5137580(5)$ published by Kim et al. (2010). The initial epoch for the primary minimum is $T_0 = 2453215.57299(83)$.

In Fig. 2, the dependence of the r.m.s. error estimate of the smoothing curve $\sigma[x_C]$ ($= \sigma_{obs}$ in Eq. (18) of Andronov (1994))is shown as a function of the degree s of trigonometric polynomial. For all three filters, the minimum of this function is seen at $s = 2$. Additional analysis using the program FDCN (FOUR-N) by Andronov (1994) had shown, that the coefficients $C_{s,2j}$ are statistically significant up to $j = 4$. Thus we have chosen $s = 4$, which corresponds to physically better phase curve (i.e. more sharp minima than maxima). For this $s = 4$, the period estimates are $0.^{\rm d}5137419(70)$, $0.^{\rm d}5137332(37)$, $0.^{\rm d}5137454(32)$. The mean weighted value is $P_{orb} = 0.5137405(23)$ and $T_0 = 2453215.5773(13)$. We also computed a “mean weighted” periodogram

$$G(f) = \sum_{i=1}^{3} w_i \cdot (1 - S_i(f))$$

with weights proportional to $w_i = (n - 1 - 2s)/(1 - S_{max,i})$, where $S_{max,i}-$ is maximal value of the periodogram for a given filter i. The minimum of this function occurs at $P = 0.^{\rm d}5137404(85)$. Although the period estimate is fairly close to a mean weighted value, the error estimate is significantly larger.

The phase light curves and the corresponding 4-th order trigonometric polynomial fits are shown in Fig. 3. The depth of the primary minimum in different filters is $\Delta_1 V = 0.^{\rm m}382(13)$, $\Delta_1 R = 0.^{\rm m}415(7)$, and $\Delta_1 I = 0.^{\rm m}363(6)$, i.e. very similar. The amplitude is at small maximum in the filter R. The depth of the secondary minimum is $\Delta_2 V = 0.^{\rm m}240(13)$, $\Delta_2 R = 0.^{\rm m}219(8)$, $\Delta_2 I = 0.^{\rm m}229(6)$ is the same within error estimates.

The phase-averaged mean brightness is $C_1 = 4.^{\rm m}035(6)$, $3.^{\rm m}365(3)$ and $2.^{\rm m}836(3)$ for V,R,I, respectively. Although there is no calibration of the comparison star, so the color indices of the object are available only in respect to this comparison star. The differences $((V-R)_{var} - (V-R)_{comp}) = 0.^{\rm m}570(7)$ and $((R-I)_{var} - (R-I)_{comp}) = 0.^{\rm m}629(4)$ are rather large, indicating that the comparison star is a blue one, and the variable is yellow or red. This is in an agreement with expectations for W UMa - type stars (e.g. Tsesevich 1971).

USNO-B1.0 1235-0097170: EA -type

This star was classified as an Algol - type variable. The coefficients of the trigonometric polynomial fit aree statistically significant while $s \leq 7$. The TP-7 fits are shown in Fig. 4. The mean weighted values are $P_{orb} = 0.^{\rm d}8698365(26)$ and $T_0 = 2453208.8503(9)$. For each of these fits, 16 parameters are determined using least squares, with estimates for the r.m.s. accuracy of the fit of $\sigma[x_C] = 0.^{\rm m}0214$, $0.^{\rm m}0154$, $0.^{\rm m}0105$, $0.^{\rm m}0085$. However, one may see apparent waves at the light curve, especially when at phases badly covered by observations. Such phenomenon is a common problem for signals with very asinusoidal shape. To improve accuracy of fits for EA variables, Andronov (2010) proposed a “New Algol Variable” (NAV) fit, which was also tested by Virnina (2010). The free parameter is the eclipse half-width $\Delta\phi$. We adopted value $\beta = 2$. To determine its statistically optimal value, we computed dependence of the "unit weight error" σ_0 on $\Delta\phi$ for filters BVRI, which is shown in Fig. 5. The minima of this test function appeared at $\Delta\phi$ from 0.089 to 0.100 with a weighted mean of 0.094. The corresponding values $\sigma[x_C]$ of $0.^{\rm m}0128$, $0.^{\rm m}0098$, $0.^{\rm m}0066$, $0.^{\rm m}0053$ are by a factor of ~ 1.6 better than for the TP fit. The fits are shown in Fig. 6. One may see a significant ellipticity effect aruguing that the red star is tidally distorted, and (because of small depth of the secondary minimum) much larger than another component.

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