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PHOTOMETRY AND THE BLAZHKO EFFECT IN THE RR Lyr VARIABLE STAR Y Vul

S. N. Udovichenko and L. E. Keir

Astronomical Observatory, Odesa National University,
Odesa, Ukraine, *udovich222@ukr.net*

ABSTRACT. The RR Lyr variable star Y Vul have been observed by using a CCD photometer during several seasons from 2011 to 2017. Nearly 5960 data points were obtained spanning over 53 nights. We found the amplitude and phase modulations with the amplitudes of 0.16 mag and 0.041 of the pulsating phase in V filter; 0.15 mag and 0.041 of the pulsating phase in R filter, respectively. The frequency Fourier analysis of the light curves with the help of Period04 software was performed, Blazhko modulation period (59.20 days) and triplet structures in the Fourier spectrum were detected. The pulsation frequency components in the Fourier spectrum were identified up to the 7th harmonic order, while the modulation side lobe frequencies – up to 9th order. The analysis of the light curves maxima resulted in the same value of the Blazhko period. The fundamental pulsation period of the star has been practically stable over a period of a hundred years.

АНОТАЦІЯ. У даній роботі ми досліджуємо змінну зорю типу RR Lyr – Y Vul, яка спостерігалась нами на протязі декількох спостережних сезонів з 2011 по 2017 роки за допомогою ПЗЗ фотометра. Було одержано біля 5960 вимірювань блиску протягом 53 ночей спостережень. Ми знайшли амплітудну і фазову модуляції кривих блиску з амплітудою 0.16 mag і 0.041 по фазі для V фільтра; 0.15 mag і 0.041 по фазі для R фільтра, відповідно. Для всіх кривих блиску був виконаний чисельний Фур'є аналіз за допомогою відомої програми для аналізу блиску змінних зір – Period04; знайдений період модуляції кривих блиску – ефект Блажко (59.20 днів) та триплетна структура Фур'є спектра. Частотні пульсаційні компоненти в Фур'є спектрі були ідентифіковані до 7 гармоніки, а модуляція в бокових пелюстках спектру – до 9 гармоніки. Аналіз моментів максимумів блиску дав аналогічний результат щодо періоду ефекта Блажко. В той же час основний фундаментальний період коливання блиску зорі був практично стабільний на протязі ста років.

Keywords: Stars: variables: RR Lyr stars – Y Vul.

1. Introduction

Y Vul (AN 1907.0004, Gaia DR1 - 286.0678990585, USNO-A2.0 1125 - 11247385), ($\alpha_{J2000.0} = 19^h04^m16.3^s$; $\delta_{J2000.0} = +24°47'19.1''$) is known as the variable star for more than hundred years, but this RRab variable has been poorly investigated. The variability of the star was explored by van Biesbroeck and Casteels (1914), and they have defined that the star belongs to RR Lyr variables. However, in spite of their detailed observations, the authors haven't deduced the light curve elements. Using observation data, reported by van Biesbroeck and Casteels, Tsesevich (1960) derived a period and epoch of Y Vul as follows:

$$MaxJD = 2419221.531 + 0^d.44941 \times E. \quad (1)$$

He pointed out the difference in height of the light curves maxima and suspected the presence of the Blazhko effect in Y Vul. Using photographic observations in the range JD 2433034-41492, Kazarovets end Shugarov (1973) determined elements of the light-curve variation more accurately:

$$MaxJD = 2438939.413 + 0^d.44945164 \times E. \quad (2)$$

Their estimated range of the light variation was $14^m.2$ - $16^m.0$ (pg). The data reported in their study for Y Vul were included to the General Catalogue of Variable Stars (GCVS) (Samus' at al. 2017) and AAVSO Variable Star Index (VSX database, https://www.aavso.org/vsx/index.php).

2. Observations

The photometric CCD observations of Y Vul were obtained at the Astronomical station near Odesa during the observation seasons in 2011-12, 2014-16 years in V filter; later on, in 2017 year the observations were performed in R filter using the 48 cm reflector AZT-3 of Astronomical observatory of Odessa National University, equipped with CCD photometer and Peltier cooler

Table 1: The magnitudes of the comparison and check stars (NOMAD).

Star	α, δ_{2000}	magB	magV	magR
comA	19 04 12	14.63	13.76	13.09
	+24 45 20	-	-	-
comB	19 04 08	12.905	12.424	12.090
	+24 45 47	-	-	-
check	19 04 15	14.40	-	14.18
	+24 46 12	-	-	-
Y Vul	19 04 16	15.180	14.680	15.070
	+24 47 19	-	-	-

(Sony chip ICX429ALL, ~600x800 pixels) in the f/4.5 Newtonian focus (Udovichenko 2012).

The datasets consists of 4290 V-band data points and 1665 Rc-band points obtaind from over 53 nights of observations. Two stars were chosen as comparison and one as check stars as close as possible in B-V color. The magnitude of comparison star comB we have took from NOMAD cataloque (NOMAD 2005). We accepted these magnitudes and measured star comA relative to star comB on our frames. The resulting magnitudes for star comA are: V = 13.76, R = 13.09 with errors of 0.02 mag. The exposure time for variable and comparison stars was chosen to except a saturation of the frame and appointed as 120 sec. The BVR magnitudes of the variable, comparison and check stars from NOMAD catalogue; are summarized in Table 2.

The standard reduction of the CCD frames were carried out by using the MUNIPACK (Motl, http://sourceforge.net/projects/c-munipack) software. The procedures for an aperture photometry is composed of the dark-level and flat-field corrections, determination of the instrumental magnitudes and precision. The magnitude of comparison star "com A" was used to convert the differential magnitudes to the corresponding value of variable. The photometry was transformed to the standard VRc Johnson-Cousins system by means of the differential photometry method (Benson 1998). The transformation coefficient was determined from observations of standard stars (Udovichenko 2012). The finding chart with market-out variable, comparison and check stars is shown in Fig. 1, the whole dataset of observations is presented in Fig. 2. The errors in individual data points vary from $0^m.005$ to $0^m.02$.

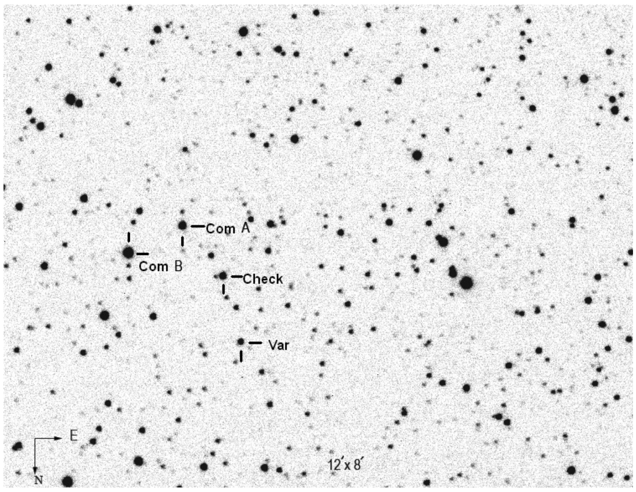

Figure 1: The finding chart of Y Vul with the variable, comparison and check stars marked.

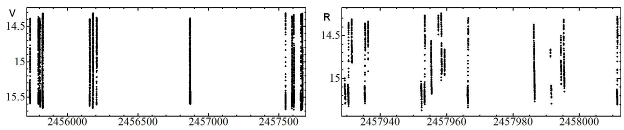

Figure 2: The all data set of observations of Y Vul.

3. Frequency spectrum analysis

All data on the light variation curves nearby maxima and minima have been approximated by polynoms of 2-7 degrees with the best fit option by using sowtware MCV (Andronov and Baklanov 1998). Then amplitudes of light variations and times of maxima have been defined. The observations of Y Vul shows the whole amplitude variation $1^m.05$ in Rc-band and $1^m.33$ in V-band. The modulation occurs at the maximum brightness and phase shift too. The brightness at maxima of the light curves in Rc-band vary from $14^m.265$ to $14^m.411$, the moderate Blazhko modulation of the amplitude reaches about 0.146; in V-band vary from $14^m.316$ to $14^m.478$, and the modulation reaches $0^m.162$. The phase shift modulation in both bands varies within about 0.041 of the pulsation phase. All light curves of the target star obtained by using V and Rc filters with the pulsating period, are shown on Fig. 3. These phase curves were computed by using GCVS elements, equation 2.

To analyse the modulation properties of the light curves for this star, we have used a common technique a Fourier decomposition. The frequency analysis was performed using a package of computer programs with sine-wave fitting by using utilize Fourier algorithms (program Period04), (Lenz and Breger 2005).

To capture longer time interval, we calculated observations, obtained with V-band and Rc-band.

The fundamental pulsation period was determined with the help of using the above-mentioned techniques as the highest peak on the Fourier amplitude spectrum. The observed harmonics and triplet were defined by pre-whitening data and Fourier analysis of the residuals. For each calculated harmonic and triplet, the signal-to-noise ratio has been estimated to retain only

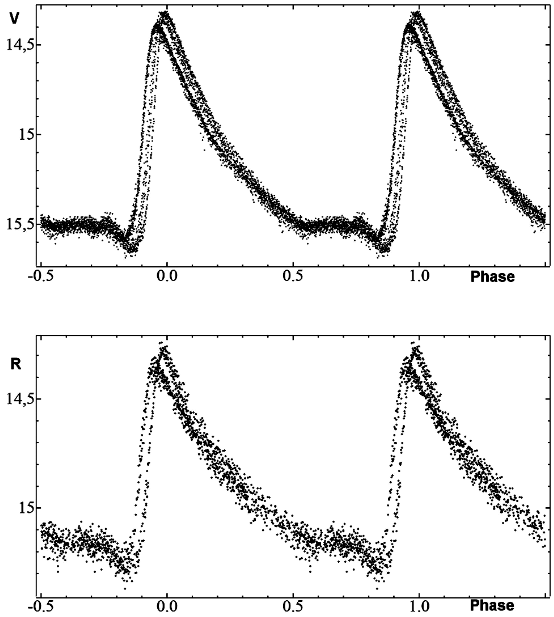

Figure 3: The phase curves of Y Vul in V and Rc filters.

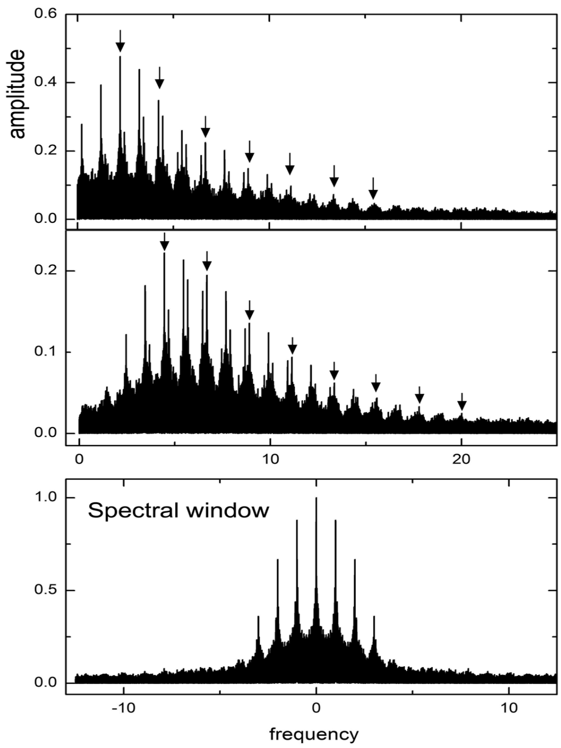

Figure 4: The Fourier amplitude spectrum of the basic frequency and after the first pre-whitening. In the above figure the arrows point to the basic pulsation frequency and its harmonics kf$_0$. In the middle figure the arrows point to the modulation frequency triplets kf$_0$±f$_m$ after the next pre-whitening. The bottom figure shows the spectral window.

significant signals greater than 4. The amplitude and phase for each frequencies, obtained with the best fitting, are given in Table 2.

The amplitude spectrum for the basic pulsating frequency and after pre-whitening are shown in Fig. 4. The harmonics of f$_0$ are significant to the 7^{th} order, triplets f$_0$±f$_m$ to 9^{th} order. The fundamental pulsating period P$_0$=0.44945177 is very close to the GCVS value. The Blazhko frequency also was determined as the difference of frequencies f$_m$ = kf$_0$ - kf$_0$±f$_m$ and given in the last column of Table 2. Some of these frequencies contains an alias frequencies ~(1/365=0.0027) as a result of the several seasons of observations (2011-17). Keeping that in mind we only used non-aliased frequencies to determine the Blazhko frequency. The average value equals 0.01689 ± 0.0004 cd^{-1}, whith corresponds to the period of 59.20 ± 0.14 day.

The amplitude asymmetry is observed in the modulation components: $Q_i = (A^+_{i1} - A^-_{i1})/(A^+_{i1} + A^-_{i1})$, where A^+_{i1} = if$_0$ + f$_m$, A^-_{i1} = if$_0$ - f$_m$. The asymmetry ratios for the first component $Q_1 = 0.36$; the triplet ratios in the side lobes $R_1 = A^+_{11}/A^-_{11} = 2.16$. The amplitudes of the pulsation components which decrease with increasing orders are smooth while the amplitudes of the modulation components decrease irregularly.

4. Light curves maxima analysis

The times of maxima in the all light curves was performed with help of fitting the light curve near the maxima by a polynomial function an order from 2 to 7. The list of observed light curves maxima presents in Table 3. The modulation Blazhko period was determined by the (O-C) period analysis (using Period04). The both method (i.e. frequency spectrum analysis and (O-C) deviation at maximum) have shown the same value of a Blazhko period. The value from the light curves maxima analysis equal 59.20 ± 0.02 days. We selected the highest observed maximum and derived the elements of the Blazhko cycle:

$$MaxHJD_{Blazhko} = 2457548.505 + 59^d.20 \times E_{Blazhko} \quad (3)$$

The O-C diagram of Y Vul versus the Blazhko phase with sinusoidal fitting curve is presented in Fig. 5 (top). The O-C values are different in 9% of the pulsation period, the magnitudes at maximuma are different in 12-14% of the V and Rc amplitude.

The O-C diagram was constructed by using all the published observational data available (Tsessevich 1960; Kazarovets and Shugarov 1973) as well as the data, obtained in this study by using the GCVS elements. The resulting diagram with linear fit is plotted in Fig. 5 (bottom). The data covers the

Table 2: Identify frequencies, amplitudes, phases and modulation frequencies f_m = kf_0 - $kf_0 \pm f_m$ of the V and Rc light curve solutions of Y Vul.

Identification	**f (cd^{-1})**	**amplitude, mag**	**phase, $rad/2\pi$**	**snr**	**f_m(cd^{-1})**
		V-band			
f_0	2.224936(2)	0.311(1)	0.084(1)	94.2	
$2f_0$	4.449874(3)	0.187(2)	0.303(2)	35.2	
$3f_0$	6.674817(3)	0.160(1)	0.845(2)	31.4	
$4f_0$	8.899735(3)	0.100(2)	0.203(3)	22.1	
$5f_0$	11.12464(1)	0.050(4)	0.63(1)	13.5	
$7f_0$	15.5717(6)	0.029(8)	0.06(2)	9.2	
f_0+f_m	2.24188(3)	0.031(9)	0.07(1)	7.1	0.01694(3)
f_0-f_m	2.20803(6)	0.027(8)	0.3(3)	6.7	0.01691(6)
$2f_0-f_m$	4.433004(9)	0.051(2)	0.268(7)	5.6	0.01687(1)
$3f_0+f_m$	6.691688(7)	0.046(2)	0.088(6)	9.3	0.01688(1)
$4f_0+f_m$	8.91661(1)	0.040(2)	0.952(9)	9.5	0.01687(1)
$6f_0-f_m$	13.33284(5)	0.038(9)	0.009(3)	11.4	0.01678(5)
$7f_0+f_m$	15.59158(2)	0.018(3)	0.71(3)	4.5	0.01702(2)
$8f_0-f_m$	17.78265(1)	0.017(2)	0.71(2)	4.0	0.01684(1)
$9f_0+f_m$	20.0076(1)	0.09(1)	0.7(3)	7.2	0.0168(1)
		R-band			
f_0	2.22491(6)	0.432(4)	0.992(2)	56.2	
$2f_0$	4.4497(1)	0.152(3)	0.715(8)	36.6	
$3f_0$	6.6744(4)	0.105(2)	0.415(4)	27.5	
$4f_0$	8.8994(4)	0.073(4)	0.813(8)	16.2	
$5f_0$	11.1235(7)	0.043(6)	0.62(2)	13.0	
$6f_0$	13.50(6)	0.022(8)	0.9(3)	5.0	
$7f_0$	15.575(1)	0.021(3)	0.19(1)	5.0	
f_0-f_m	2.2094(3)	0.038(4)	0.17(1)	6.9	0.0151(3)
$2f_0+f_m$	4.465(4)	0.035(9)	0.9(3)	8.4	0.015(4)
$3f_0-f_m$	6.659(2)	0.037(8)	0.7(1)	9.6	0.016(2)
$4f_0+f_m$	8.916(4)	0.038(3)	0.30(1)	8.4	0.016(4)
$5f_0-f_m$	11.109(2)	0.028(9)	0.6(1)	8.3	0.016(2)
$8f_0-f_m$	17.782(4)	0.016(3)	0.4(1)	4.6	0.017(4)

period of a hundred years. The O-C difference over such long period less than 0.02 day, which is less than the Blazhko phase change. It allows to assume, that Y Vul has practically no secular period changes. The scattering of dots is due to the Blazhko effect.

5. Conclusions

This paper describes the modulation of the light curves of a RR Lyrae variable Y Vul. Using the data obtained from the several observational seasons, we have found the Blazhko effect for the pulsating in the fundamental mode. The amplitude of the maximum brightness variation reaches $0^m.162$ with V filter and $0^m.146$ in Rc filter; the phase shift is 0.041 of pulsation phase. Using the Fourier analysis for these data we have derived the fundamental pulsating period of 0.4494517 ± 0.000001 day. The Blazhko period was defined using the O-C value at maxima and frequency spectrum analysis. The average period equal 59.20 ± 0.02 days. The modulation of the Y Vul light curves are described by the triplet frequencies $kf_0 \pm f_m$ and the modulation frequency f_m. In the frequency spectrum

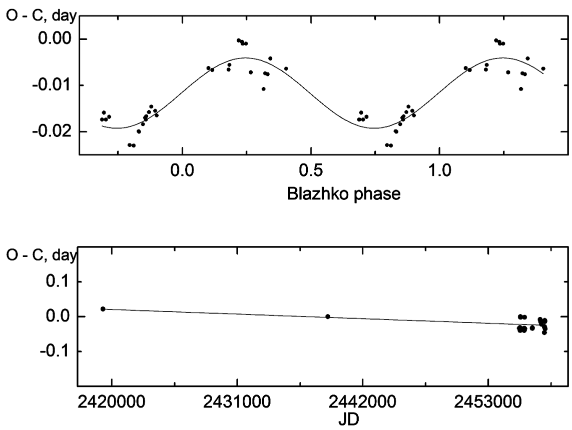

Figure 5: The O-C (day) diagram of Y Vul versus Blazhko phase with the sinusoidal fitting curve (top figure). The O-C (day) diagram of Y Vul during over a hundred years with the linear fitting (bottom figure).

Table 3: List of measured maxima of Y Vul

Maximum HJD	Error	Magnitude (V-C)	Error	Cycle	O - C	Phase	Error	Filter
2455735.4040	0.00019	0.6209	0.0028	37369	-0.0168	-0.0374	0.0004	V
2455793.3841	0.00021	0.6288	0.0027	37498	-0.0159	-0.0354	0.0004	V
2455801.4702	0.00025	0.6499	0.0034	37516	-0.0199	-0.0444	0.0005	V
2455802.3706	0.00018	0.6315	0.0027	37518	-0.0184	-0.0410	0.0003	V
2455805.5187	0.00071	0.6752	0.0112	37525	-0.0165	-0.0367	0.0015	V
2455824.4119	0.00028	0.5622	0.0049	37567	-0.0002	-0.0006	0.0006	V
2455825.3101	0.00023	0.5534	0.0034	37569	-0.0010	-0.0022	0.0005	V
2456156.5371	0.00031	0.6479	0.0034	38306	-0.0198	-0.0442	0.0007	V
2456158.3380	0.00023	0.6349	0.0030	38310	-0.0167	-0.0372	0.0005	V
2456180.3773	0.00020	0.5633	0.0033	38359	-0.0006	-0.0013	0.0004	V
2456181.2759	0.00026	0.5609	0.0041	38361	-0.0009	-0.0021	0.0005	V
2456207.3276	0.00048	0.6349	0.0055	38419	-0.0174	-0.0387	0.0010	V
2456208.2265	0.00024	0.6276	0.0021	38421	-0.0174	-0.0387	0.0005	V
2456868.4714	0.00023	0.6360	0.0030	39890	-0.0169	-0.0377	0.0005	V
2456869.3714	0.00022	0.6290	0.0029	39892	-0.0158	-0.0352	0.0005	V
2457548.5045	0.00027	0.5528	0.0048	41403	-0.0041	-0.0092	0.0006	V
2457593.4476	0.00031	0.6061	0.0040	41503	-0.0063	-0.0140	0.0007	V
2457594.3460	0.00030	0.6009	0.0050	41505	-0.0067	-0.0150	0.0006	V
2457606.4806	0.00022	0.5664	0.0027	41532	-0.0073	-0.0163	0.0004	V
2457657.2694	0.00028	0.5710	0.0045	41645	-0.0066	-0.0147	0.0006	V
2457665.3550	0.00029	0.5695	0.0044	41663	-0.0111	-0.0248	0.0006	V
2457666.2574	0.00040	0.5599	0.0069	41665	-0.0076	-0.0169	0.0009	V
2457899.5228	0.00043	0.5565	0.0078	42184	-0.0076	-0.0170	0.0010	V
2457930.5197	0.00033	1.2740	0.0062	42253	-0.0229	-0.0509	0.0007	R
2457931.4185	0.00038	1.2249	0.0043	42255	-0.0229	-0.0510	0.0008	R
2457935.4719	0.00051	1.2772	0.0060	42264	-0.0146	-0.0325	0.0011	R
2457936.3699	0.00073	1.2768	0.0075	42266	-0.0155	-0.0345	0.0016	R
2457953.4590	0.00034	1.1902	0.0054	42304	-0.0055	-0.0124	0.0007	R
2457958.4014	0.00070	1.1700	0.0064	42315	-0.0071	-0.0159	0.0015	R
2457966.4924	0.00036	1.1909	0.0074	42333	-0.0063	-0.0141	0.0008	R
2457993.4484	0.00066	1.2576	0.0089	42393	-0.0174	-0.0388	0.0014	R

the pulsation harmonic components are detected up to the 7^{th} order; the modulation side lobe frequencies are detected up to 9^{th} order. Thirty pulsation maxima from the observed light curves have been measured. The fundamental pulsation period of the star has been practically stable over a period of a hundred years.

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