PROCEEDINGS OF SCIENCE

Photometric monitoring of eclipsing cataclysmic variables

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In this work, we process optical photometric monitoring of known eclipsing dwarf novae and polars, whose brightness variations amount to $\approx 1^m$ or more due to the varying matter transfer rates in the systems. The aim of the monitoring is to select objects that have low accretion rates at the time of observations. The observations are carried out with the 28-cm reflector of the North Caucasian Astronomical Station of KFU. The V and R_C band magnitudes of a sample of dwarf novae and polars are determined and then compared with literature data. Magnitudes corresponding to low accretion rates are registered in EX Dra, GY Cnc, IP Peg and CRTS J054558.3+022106 dwarf novae; V1309 Ori, HU Aqr, V808 Aur and VV Pup polars, on the contrary, are all detected only with high accretion rates.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

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PoS(MUTO2022)039

1. Introduction

Cataclysmic variable stars (CVs; see Warner 1995 [1] for more details) are close binary stars composed of a white dwarf (primary) and a low-mass main-sequence star (secondary). Mass is transferred from the secondary star to the white dwarf, forming an accretion disk around the primary. If the white dwarf has a strong magnetic field ($B \sim 10^7$–10^8 G), the accreting matter becomes a stream channeled by the magnetic field of the primary and transferred to one or both of its magnetic poles; such CVs are named polars.

The objects of our research are CVs of two types: dwarf novae (a type of CVs with accretion disks) and the above-mentioned polars. Characteristic orbital periods and brightness amplitudes within these periods are 1.2–12 hours and 0.2–0.3^m or more for dwarf novae and 1.5–4 hours and $\approx 1^m$ for polars.

In addition to orbital brightness variations, dwarf novae show outbursts repeating at comparable intervals of time (in the range of 10 days to dozens of months). During these outbursts, the brightness increases by 2–5^m. Polars show spontaneous brightening up to 3^m. These non orbital brightness variations are related to accretion rate changes. Close binary systems are not optically resolved, and therefore the fundamental parameters of the components are usually determined indirectly by the radiation of the entire system. However, some such systems are eclipsing. This manifests as primary (when the white dwarf is eclipsed by the fainter star) and secondary eclipses on their phase-resolved light curves.

Dwarf novae have quiescent and outburst states while polars have low, medium and high states depending on the accretion rates. At high accretion rates, the transferring matter has a high brightness. In the case of a dwarf nova outburst, radiation from the accretion disk dominates. This is clearly shown in the light curves of EX Dra dwarf nova introduced by Voloshina et al. 2019 [2]. In the case of a polar at high accretion rates, the accretion stream and spots on the white dwarf surface make a contribution to the radiation of the system; they also distort the shape of the primary eclipse. At low rates, this radiation is small, so the light curve reaches its minimum at the moment when the cold star completely eclipses the white dwarf. One can see this, for example, in the light curves of the V808 Aur polar in different states obtained by Schwope et al. 2015 [3].

The low state of dwarf novae and polars is of particular interest to us. From the duration of the eclipse onsets and exits from the primary eclipse at low accretion rates, it is possible to determine the radius of the white dwarf directly. However, this requires observations with high time-resolution. But first one must make sure that the object has precisely low accretion rates.

2. Observations and data processing

In order to estimate the state of a dwarf nova or a polar, observing the object with a small telescope is sufficient. Among such telescopes is the Celestron Schmidt-Cassegrain telescope SC 280/2800 (280mm aperture and 2800mm focal length) with a 5.4-micron pixel QSI 583ws CCD camera with a $0.68° \times 0.45°$ field of view, located at the Astronomical station of the Kazan (Volga region) Federal University in the North Caucasus, Russia. We have carried out photometric monitoring of the known eclipsing dwarf novae and polars and selected the CVs that had been in a quiescent or low state at the time of observations since January 27th, 2020. As part of this work, we have processed the data obtained up to April 26th, 2022. During observations of one field, from 3 to 10 frames were obtained with exposures from 30 to 300 seconds in the Green and Red bands, which are close to the V and R_C bands of the Johnson-Cousins photometric system.

We have monitored four relatively bright dwarf novae and four polars; their orbital periods taken from the AAVSO VSX service[1] and the frequencies of the dwarf novae outbursts are presented in tables 1 and 2. Our photometric data do not cover the orbital periods of the CVs, because we mainly calculate their mean out–of–eclipse magnitudes.

Table 1: Orbital periods and frequencies of the outburts of the dwarf novae.

Dwarf nova	Orbital period, hours	Frequency of the outburts (Source)
EX Dra	5.0384784	10–30 days (Voloshina et al. 2019 [2])
GY Cnc	3.796946	210–270 days (Voloshina et al. 2017 [4])
IP Peg	4.210608	few months (Froning et al. 1999 [5])
CRTS J054558.3+022106	2.9033184	≈200–400 days (Miszalski et al. 2016 [6])

Table 2: Orbital periods of the polars

Polar	Orbital period, hours
V1309 Ori	7.9827
HU Aqr	2.08368999
V808 Aur	1.953017
VV Pup	1.67392

CCD data reduction is performed in ccdproc Python-package (Craig et al. 2017 [7]). Photometric data are solved for accurate WCS information using Astrometry.net (Lang et al. 2010 [8]). The optimal accuracy of the astrometry is achieved when the degree of the interpolating polynomial equals 6; this astrometric accuracy is 1-2.5”. Automatic source detection is carried out using the Source Extractor software (Bertin et al. 1996 [9]) with the optimal input parameters (the area used to estimate the background – 160 pixels, detection threshold – 3σ, minimal number of pixels for detection – 12 pixels). If a CV is detected in a frame, its magnitude corresponds to the flux inside its automatically matched elliptical Kron aperture. Otherwise the limiting magnitude of the frame is estimated, which corresponds to the flux under a symmetrical Gaussian curve with the field stars FWHM, when the curve includes a minimal number of pixels above the detection threshold. The limiting magnitude as well as the astrometric accuracy depend on the object guiding quality of the telescope and the atmospheric conditions.

We have performed differential photometry and determined the V and R_C band magnitudes of the CVs. Reference stars with known magnitudes taken from the AAVSO VSP service[2] are also detected in each frame and extracted. The coordinates and magnitudes of the reference stars are presented in table 3. The photometric accuracy is 0.03–0.1^m; this value is acceptable for our research.

[1]URL: https://app.aavso.org/vsx/
[2]URL: https://app.aavso.org/vsp/

PoS(MUTO2022)039

Table 3: Right ascensions, declinations and V and R_C magnitudes of the reference stars

Field with the CV	α_{ref}	δ_{ref}	V_{ref}	$R_{C\ ref}$
EX Dra	$18^h03^m37^s.55$	$67°57'01''.7$	12.038±0.013	11.832±0.021
GY Cnc	$09^h09^m57^s.80$	$18°49'02''.9$	13.740±0.005	13.665±0.034
IP Peg	$23^h23^m39^s.01$	$18°32'36''.4$	14.900	14.415±0.072
CRTS J054558.3+022106	$05^h45^m45^s.21$	$2°26'32''.7$	13.883±0.006	13.693±0.051
V1309 Ori	$05^h15^m33^s.78$	$1°05'06''.3$	14.201±0.012	13.822±0.014
HU Aqr	$21^h07^m59^s.08$	$-5°18'49''.5$	14.627±0.024	13.228±0.025
V808 Aur	$07^h11^m42^s.31$	$43°57'11''.4$	12.154±0.014	11.817±0.020
VV Pup	$08^h15^m01^s68$	$-19°02'18''.5$	13.356±0.014	13.072±0.035

3. Results

3.1 Dwarf novae IP Peg, GY Cnc and CRTS J054558.3+022106

Dwarf novae IP Peg and GY Cnc are detected in all the frames. We have determined their mean magnitudes obtained during one night of observations. The result is (15.0±0.1)–(15.8±0.2) and (15.6±0.2)–(16.3±0.2) in the V band and (14.5±0.1)–(14.65±0.03) and (15.5±0.5)–(15.74±0.04) in the R_C band for IP Peg and GY Cnc, respectively. Dwarf nova CRTS J054558.3+022106 is not detected in any frame among our photometric data, that is why we have estimated the limiting magnitude: its range is 14.8 – 17.3 in the V band and 14.6 – 16.0 in the R_C band.

The resulting magnitudes are compared to the dwarf novae long-term V band light curves from the Catalina Real-Time Transient Survey (Drake et al. 2009 [10]). The light curves show their noticeable outbursts; the quiescent state of IP Peg, GY Cnc and CRTS J054558.3+022106 is observed while their magnitudes do not exceed $\approx 14^m$, $\approx 15^m$ and $\approx 16^m$, respectively. Based on this, we infer that IP Peg, GY Cnc, as well as CRTS J054558.3+022106 at least on some nights, were observed in the quiescent state.

3.2 Dwarf nova EX Dra

The photometric data of EX Dra dwarf novae obtained on February 11th and April 24th, 2022, cover its primary eclipse, the light curves are presented in figure 1. For other data the mean magnitudes are calculated, they are presented in table 4. We have compared these results with EX Dra R_C band light curves from Voloshina et al. 2019 [2]. The comparison demonstrates that our data covering the eclipse show the quiescent state of EX Dra. Additionally, this state was caught on 4 other nights, and the outbursts were detected on 2 nights. It is worth noting that this dwarf nova exhibits relatively frequent and prolonged outbursts, so for a more accurate state estimation, it is certainly worth observing EX Dra for a longer time period, since the state can be determined from the morphology of the phase–resolved light curve.

3.3 Polars V1309 Ori, HU Aqr, V808 Aur and VV Pup

Our telescope with a small aperture allows us to obtain only out-of-eclipse magnitudes of the polars, because their eclipse brightness is too low and beyond the capabilities of the instrument.

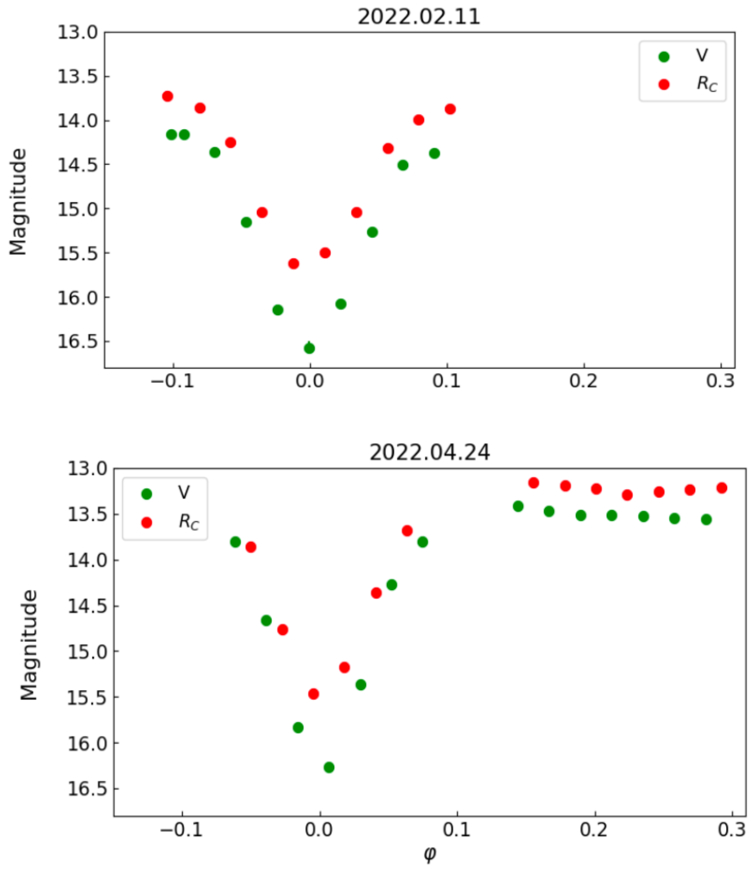

Figure 1: The phase-resolved light curves of EX Dra dwarf nova obtained on February 11th and on April 24th, 2022.

Table 4: EX Dra observation details and mean magnitudes.

Date	Frames number	Exp. time	Orbital phases	V	R_C	State
2021.10.22	5	120	0.25717–0.32879	14.47±0.04	14.10±0.02	Quiescence
2021.11.08	8	120	-0.28360– -0.15498	13.20±0.04	12.90±0.03	Outburst
2022.03.28	7	30	0.21023–0.25081	13.49±0.05	13.11±0.02	Quiescence
2022.03.30	7	30	-0.20185– -0.16133	13.10±0.03	12.88±0.03	Outburst
2022.04.09	7	180	-0.26232– -0.11435	15.05±0.04	14.58±0.02	Quiescence
2022.04.16	7	180	0.33092–0.4789	15.34±0.09	14.82±0.02	Quiescence

We have determined the mean magnitudes of four polars in our sample and compared them to out-of-eclipse magnitudes of the corresponding objects in different states from the literature. Table 5 shows the eclipse and out-of-eclipse magnitudes in the low, medium and high states for the polars from the literature; the sources are indicated. The mean magnitude ranges according to our data are presented in table 6. As is evident from the V and R_C band magnitudes, all four polars were observed in a high state. The exception is the data for V808 Aur from February 10th, 2020, when the object was not detected in the frames and its magnitude was below 16.42^m in the V band; V808 Aur may have been caught in the low state, which is of interest to us.

Table 5: Eclipse and out–of-eclipse magnitudes of the polars in different states from the literature.

Polar	Eclipse magnitude	Out-of-eclipse magnitude	Source
V1309 Ori	$V \approx 17.6$, $R \approx 16.4$ (high)	high: $V<16$, $R<15$	Katajainen et al. 2003 [11]
HU Aqr	$V \lesssim 20.5$	medium (close to low): $V \approx 17$-18	Somova et al. 2004 [12]
V808 Aur	$V \approx 21.0$	high: $R_C \lesssim <15$ medium: $R_C \approx 15$-16 low: $V \gtrsim 17.6$, $R_C \gtrsim 16.3$	Thorne et al. 2010 [13] Katysheva, Shugarov 2012 [14]
VV Pup	$V \approx 19.6$	high: $V, R \lesssim <16$ medium: $V \approx 16$-18 low: $V \gtrsim 18$	Szkody et al. 1983 [15] Campbell et al. 2008 [16] Mason et al. 2008 [17]

Table 6: Mean magnitudes of the polars.

Polar	V	R_C
V1309 Ori	(15.56±0.05) - (16.3±0.1)	(15.40±0.01) - (15.6±0.1)
HU Aqr	(16.11±0.07) - (16.3±0.2)	(15.64±0.07) - (16.00±0.07)
V808 Aur	2020.02.10: <16.42±0.05 on other nights: (14.7±0.3) - (15.8±0.2)	(14.44±0.04) - (15.6±0.4)
VV Pup	(14.60±0.06) - (15.72±0.04)	(14.44±0.06) - (15.1±0.2)

Acknowledgements

This work was supported by the Russian Foundation for Basic Research via grant No. 19–32–60021.

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