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V1006 Cyg: SU UMa-type dwarf nova in the period gap that wobbles between subclasses

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Abstract. We present a result of the multi-longitude campaign on a photometric investigation of the SU UMa-type dwarf nova in the period gap, V1006 Cyg in 2023. It displayed a long-lasted standstill (a feature of Z Cam-type stars) terminated by a long outburst (a feature of IW And stars). The long outburst did not have superhumps (a feature of SS Cyg-type stars) but showed orbital 0.09837(22) d periodicity instead. Color-color diagrams indicate that layers of the disk of different temperatures contribute to the total radiation of the system. In particular, a large contribution from the innermost hot layers is detected in quiescence.

Key words: accretion, accretion disks – cataclysmic variables – stars: dwarf novae – stars: individual: V1006 Cyg

1. Introduction

Non-magnetic cataclysmic variable stars (CVs) are close binary systems where a late-type component filling its Roche lobe loses matter on the white dwarf. CVs could be divided into three subclasses: SU UMa-type, Z Cam-type and U Gem-type (or SS Cyg-type). Originally this division was based on the morphology of the light curves (Warner, 1995). According to Warner, a distinctive feature of Z Cam-type stars is protracted standstills that are terminated by fading. There is a subgroup of "anomalous" Z Cam-type stars, IW And-type objects, displaying standstill terminated by brightening (Kato, 2019). SU UMa stars have two types of outbursts – superoutbursts lasting a couple of weeks and normal outbursts which are less bright and as short as 2-4 d; SS Cyg-type stars are neither Z Cam nor SU UMa stars. Osaki (2005) proposed that different outburst behaviour of non-magnetic CVs may be explained in a framework of disk instability model which uses two instabilities: thermal instability and tidal instability of accretion disk. There are two parameters characterizing accretion disks: mass transfer rate from the secondary component and the orbital period (or mass ratio). A period gap is a borderline region that determines the ability of CVs to undergo tidal instability (below the gap) or not (above the gap). Another borderline is a critical mass transfer rate $\dot{M}_{crit}$ (Osaki, 1996). While CVs with mass-transfer rate higher than $\dot{M}_{crit}$ are hot and exhibit "stable" disks, CVs with mass-transfer rate less than $\dot{M}_{crit}$, are in the region of thermal instability and show outbursts. Thus, accretion disks of U-Gem-type stars that have orbital periods longer than those in the "gap", are thermally unstable but tidally stable. SU UMa-type stars with orbital periods less than the gap have disks that are both thermally and tidally unstable. Z Cam-type stars are located close to the $\dot{M}_{crit}$ and with periods above the gap. So the period gap is a region where these two instabilities intersect and therefore there is a possibility that some CVs in this region may have properties of neighboring subclasses.

As a dwarf nova V1006 Cyg is known since 1963 (Hoffmeister, 1963). Sheets et al. (2007) found that the orbital period of binary is 0.09903(9) d which classified it as a dwarf nova in the period gap. The 2006 outburst was suspected to be a superoutburst. Finally, V1006 Cyg was identified as the SU UMa-type dwarf nova in the period gap based on the results of studies during the 2015 superoutburst (Kato et al., 2016). V1006 Cyg got attention not only by its localization in the period gap but also by detection in 2007, 2009 and 2017 of long outbursts without superhumps but with orbital-related brightness variations (Pavlenko et al., 2014, 2018). It was also found that this star showed three types of outbursts – normal, long normal and superoutbursts (Kato et al., 2016). A diversity of normal outbursts makes V1006 Cygnus look like the SS Cyg-type star.

2. Observations and data reduction

CCD photometry of V1006 Cyg has been carried out with eight telescopes at seven observatories during 72 nights in 2023. Most of the observations were made in unfiltered light corrected to R_C. In selected nights of outburst and quiescence, V1006 Cyg was observed in the Johnson-Cousins $UBVR_CI_C$ colour bands (see Tab.1). We used the $UBVR_CI_C$ values of comparison star No 140 as in the paper by Pavlenko et al. (2018) and $U = 15^m.58$ for this star obtained relatively to the stars with known magnitudes in the vicinity of CH Cyg (Henden & Munari, 2006). Standard data reduction included flat-fielding, bias and dark signal removal. The MAXIM DL and Goranskij (http://www.vgoranskij.net/software/) WinFit packages were used. A periodogram analysis was done with the help of the Stellingwerf method implemented in the Pelt (1992) package.

3. 2023 overall light curve

Our observations are shown in Fig 1. They start from JD 2460076 capturing the decline of outburst superposed on the quiescent state at mean brightness about $R_C \sim 16^m.4$ that turned out to be $1^m - 1^m.5$ magnitudes brighter compared to known previous observations in 2015-2017 (Pavlenko et al., 2018). This "bright" quiescence which lasted $\sim$ three weeks, was terminated by the next long outburst with a duration of 10 d and amplitude of $\sim 2^m.5$. This behaviour resembles those in the IW And-type dwarf novae, where a quiescence terminates by outburst. After the end of the outburst, V1006 Cyg returned to its "usual" quiescent state, the return itself lasted about a couple of weeks. We did not detect any outburst during $\sim$ 3.5 months after the long outburst. Note that during the 2015-2017 quiescence there was a brief episode of increased brightness around normal outburst No 3 (see Fig. 1 in Pavlenko et al. (2018)).

4. Brightness variations in outburst and quiescence

During the long outburst short-term periodical brightness variations were detected. The outburst and nightly light curves are shown in Fig 2. It is seen that these variations existed on the two nights at the top of the outburst and one night at the outburst decline (HJD 2460108-2460110). Variations at the JD 2460111 were not detected. A periodogram calculated for data of these three nights after the removal of the trend corresponding to the outburst profile, is shown in Fig 3, a. The most significant peak on the periodogram corresponds to the 0.09837(22) d period which, within the limits of error, coincides with known orbital period estimates. The phased light curve was calculated using the zero-epoch HJD=24060108.40317 and period 0.09837 d (Fig 3, b).

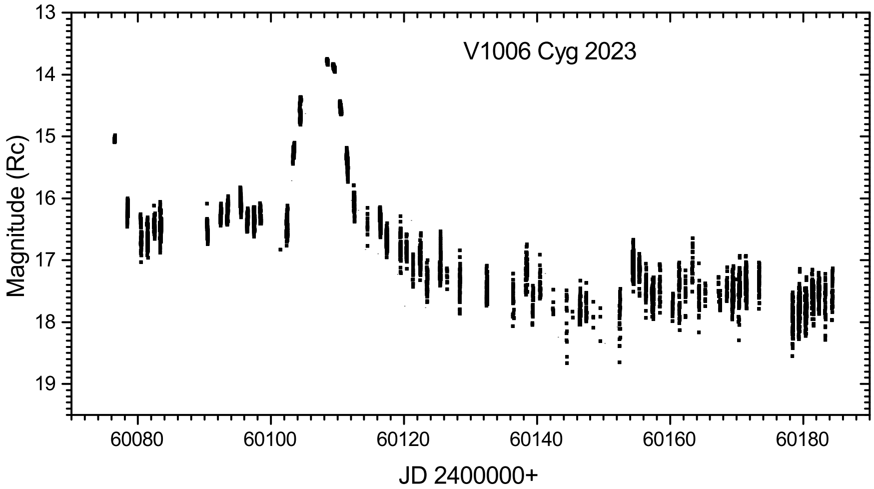

Figure 1. Long-term 2023 light curve.

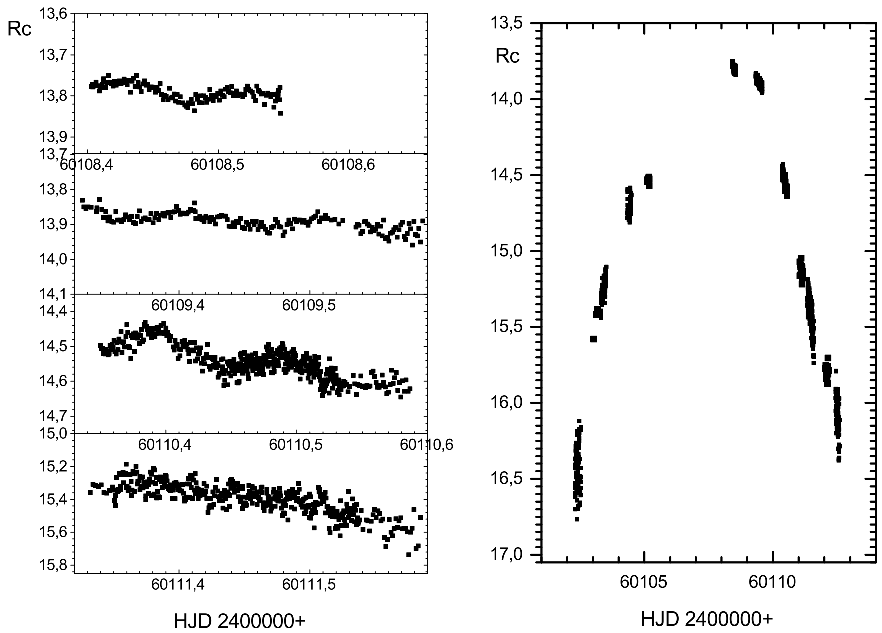

Figure 2. Short-term periodic variations in the R_{C} band (left) during the long outburst (right).

A mean R_C light curve has a symmetric profile and amplitude of $0^m.05$. Note that 2007 and 2009 orbital light curves displayed similar profiles (Pavlenko et al., 2014).

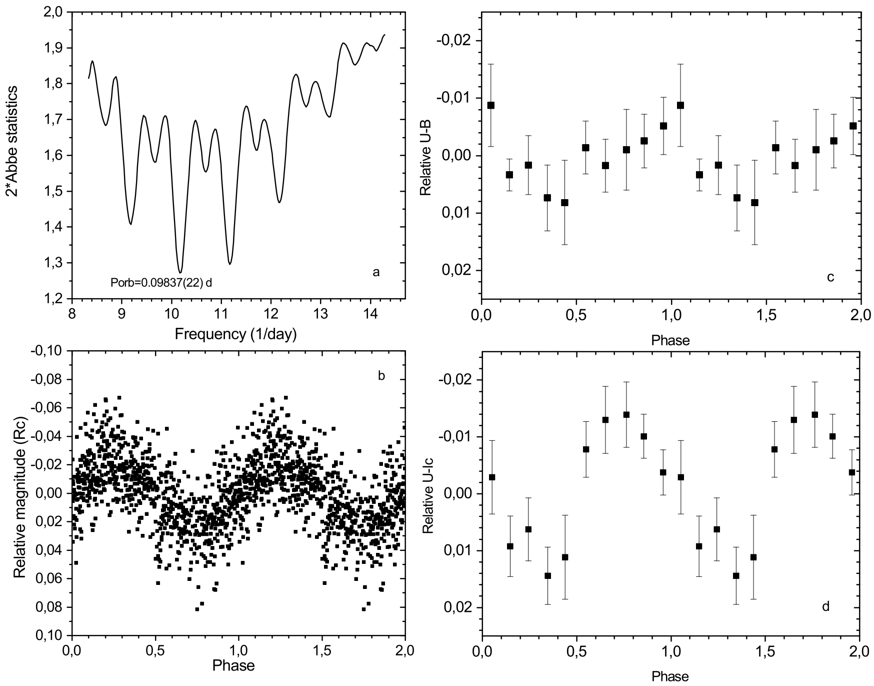

Figure 3. Orbital period of V1006 Cyg during the long outburst. Periodogram (a), R_C data from HJD 2460108, 2460109, 2460110, and mean $U-B$ and $U-I_C$ data from HJD 2460108, 2460109 folded on the orbital period 0.09837 d (b, c, d respectively).

For HJD 2460108 and 2460109 we calculated phase-resolved colour indices after removing the trend corresponding to the outburst profile. We have done this procedure for the closest colour bands $U-B$ and for the most distant wavelengths $U-I_C$ (see Fig 3, c and d, respectively). The mean amplitude in V is $0^m.016$. The $U-B$ and $U-I_C$ light curves displayed dependence on the phase of the orbital period with amplitudes $0^m.012$ in $U-B$ and $0^m.028$ in $U-I_C$. The blue peak of both $U-B$ and especially $U-I_C$ curves coincides with a minimum of the V light curve. We interpret these light curves as being caused by a hot spot on the disk. However, this behaviour is opposite to that observed in light curves, where the main contribution to the emission comes from the hot spot. We suppose that the ultraviolet excess at minimum is caused by a contribution from the innermost part of the accretion disk that is hotter than the hot spot.

Characteristic of the quiescence is the presence of quasi-periodic oscillations (QPOs) in a range of minutes-hours. An example of short-term QPOs is shown in Fig 4,a. These QPOs were coherent on a scale of at least about an hour (see Fig 4, b). As during 2016 quiescence, no evidence of an orbital period was found in 2023 quiescence (Pavlenko et al., 2018).

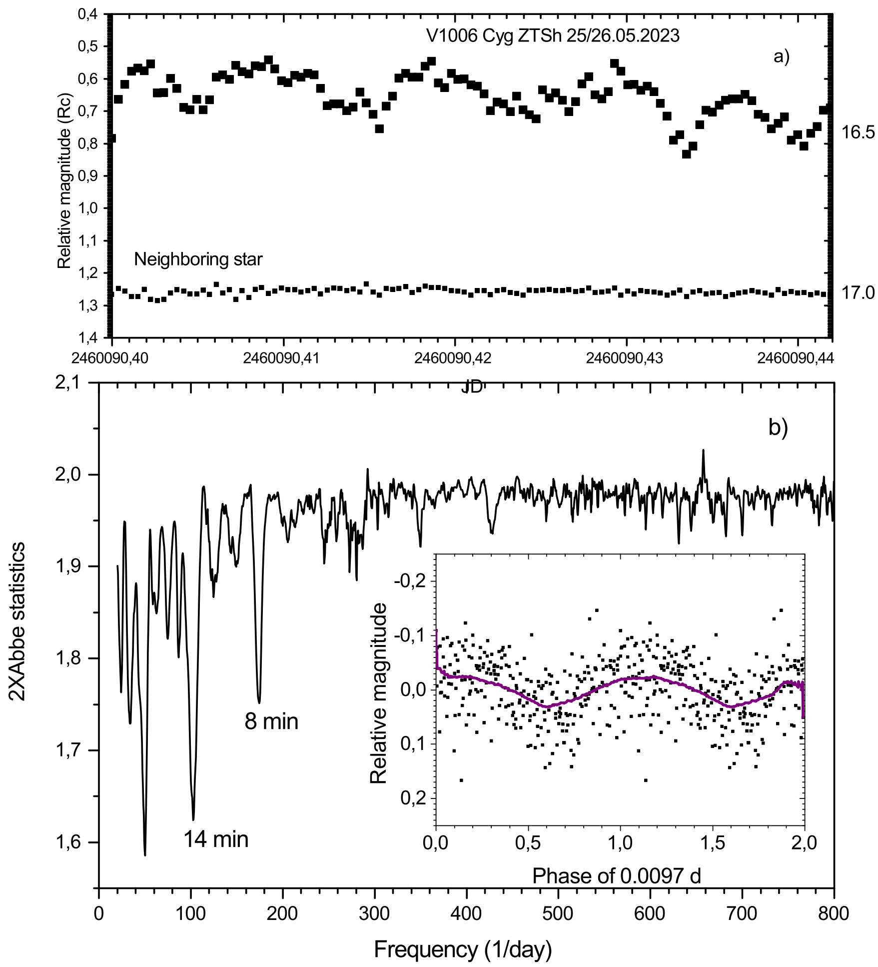

Figure 4. Example of nightly light curve in quiescence displaying short-term QPOs (a); periodogram and data folded on the 14-min period (b).

5. Colour variations

Colour-colour diagrams including changes in colour indices of V1006 Cyg during the transition from outburst to quiescence are shown in Fig 5. One could see that in U-B the object has a higher temperature at quiescence than at outburst. The opposite behaviour is observed in the region of longer wavelengths: radiation of the object is hotter at outburst compared to quiescence. This may mean that the radiation can come from the parts of the disk with different temperatures. In quiescence, the disk returns to a cold state, and its size decreases significantly. In this case, it is natural that the contribution to the total radiation of the hottest innermost layers of the disk increases. This can explain the ultraviolet excess in a quiet state in the $U-B, B-V$ diagram. Similar behaviour of colour indices was noted by Golysheva & Shugarov (2014) for the dwarf nova PNV J19150199+071947.

Table 1. Journal of observations

HJD 2460000+ (start - end)	Observatory/telescope	CCD	N
076.460 076.556	SLO/0.60m	FLI ML3041	74
078.353 078.523	SLO/0.60m	FLI ML3041	73
080.313 - 080.549	CrAO/0.38m	Apogee E47	94
081.358 - 081.536	CrAO/0.38m	Apogee E47	82
082.386 - 082.545	CrAO/0.38m	Apogee E47	76
083.295 - 083.545	CrAO/0.38m	Apogee E47	118
090.347	SLO/0.60m	FLI ML3041	1
090.389 - 090.485	CrAO/2.60m	Apogee E47	252
092.389 092.522	SLO/0.60m	FLI ML3041	99
093.356 - 093.554	SLO/0.60m	FLI ML3041	120
095.364 - 095.488	SLO/0.60m	FLI ML3041	124
096.389 - 096.541	SLO/0.60m	FLI ML3041	118
097.360 - 097.545	SLO/0.60m	FLI ML3041	105
098.329 098.516	KAZ/1.10m m	QSI 583wsg	51
101.380 - 101.471	CrAO/0.38m	Apogee E47	2
102.301 - 102.525	CrAO/0.38m	Apogee E47	98
103.031 - 103.186	JAP/0.50m	Apogee Alta F6	4
103.307 - 103.521	CrAO/0.38m	Apogee E47	102
104.335 - 104.496	CrAO/0.38m	Apogee E47	77
104.299 104.525	KAZ/1.10m m	QSI 583wsg	61
105.110 - 105.191	JAP/0.50m	Apogee Alta F6	11
108.403 - 108.546	SLO/0.60m	FLI ML3041	129
109.326 - 109.419	SLO/0.60m	FLI ML3041	133
110.350 - 110.532	SLO1/0.60m	Atik 383L	237
111.041 - 111.148	JAP/0.50m	Apogee Alta F6	14

Table 1. Journal of observations (continued)

HJD 2460000+ (start - end)	Observatory/telescope	CCD	N
111.350 - 111.537	SLO1/0.60	Atik 383L	243
111.476 - 111.584	Bel/0.40	FLI 16803	84
111.332 - 111.466	CrAO/0.38m	Apogee E47	51
112.046 - 112.151	JAP/0.50mm	Apogee Alta F6	14
112.461 - 112.527	CrAO/0.38m	Apogee E47	32
114.495 - 114.531	CrAO/0.38m	Apogee E47	18
116.468 - 116.521	CrAO/0.38m	Apogee E47	141
117.390 - 117.481	CrAO/0.38m	Apogee E47	126
119.395 - 119.533	CrAO/0.38m	Apogee E47	64
120.335 - 120.437	CrAO/0.38m	Apogee E47	38
121.323 - 121.365	CrAO/0.38m	Apogee E47	21
122.364 - 122.526	SLO/0.60m	FLI ML3041	108
123.401 - 123.537	SLO/0.60m	FLI ML3041	60
125.371 - 125.521	SLO/0.60m	FLI ML3041	97
126.447 - 126.496	CrAO/0.38m	Apogee E47	10
128.361 - 128.425	SLO/0.60m	FLI ML3041	57
132.371 - 132.476	SLO/0.60m	FLI ML3041	85
136.372 - 136.507	CrAO/2.60m	Apogee E47	26
138.296 - 138.546	CrAO/2.60m	Apogee E47	78
139.309 - 139.397	CrAO/2.60m	Apogee E47	30
140.407 140.521	KAZ/1.10m	QSI 583wsg	24
140.443 - 140.492	CrAO/0.38m	Apogee E47	3
142.391 142.410	KAZ/1.10m	QSI 583wsg	6
142.409	CrAO/0.38m	Apogee E47	1
144.429 - 144.478	KAZ/1.10m	QSI 583wsg	13
144.507	CrAO/0.38m	Apogee E47	1
145.336 145.358	KAZ/1.10m	QSI 583wsg	2
146.384 - 146.508	SLO/0.60m	FLI ML3041	80
146.422 146.465	KAZ/1.10m	QSI 583wsg	7
147.352 - 147.477	CrAO/0.38m	Apogee E47	25
148.428 148.464	KAZ/1.10m	QSI 583wsg	4
149.491 - 149.524	CrAO/0.38m	Apogee E47	3
152.381 - 152.510	SLO/0.60m	FLI ML3041	29
154.359 - 154.541	CrAO/0.38m	Apogee E47	141
154.378 - 154.382	SLO/0.60m	FLI ML3041	2
155.338 - 155.377	SLO/0.60m	FLI ML3041	30
155.361 - 155.404	CrAO/0.38m	Apogee E47	21
156.344 - 156.370	CrAO/0.38m	Apogee E47	13
156.347 - 156.416	SLO/0.60m	FLI ML3041	35
157.393 - 157.420	SLO/0.60m	FLI ML3041	31

Table 1. Journal of observations (continued)

HJD 2460000+ (start - end)	Observatory/telescope	CCD	N
160.344 - 160.425	SLO/0.60m	FLI ML3041	29
161.326 - 161.428	CrAO/0.38m	Apogee E47	49
162.308 - 162.344	CrAO/0.38m	Apogee E47	18
163.317 - 163.377	CrAO/0.38m	Apogee E47	29
164.314 - 164.386	CrAO/0.38m	Apogee E47	35
165.272 - 165.305	CrAO/2.60m	Apogee E47	11
167.269 - 167.320	CrAO/2.60m	Apogee E47	14
169.331 - 169.413	CrAO/0.38m	Apogee E47	40
170.311 - 170.397	CrAO/0.38m	Apogee E47	42
173.341 - 173.430	CrAO/0.38m	Apogee E47	43
178.348 - 178.494	CrAO/0.38m	Apogee E47	67
179.295 - 179.543	CrAO/0.38m	Apogee E47	129
180.275 - 180.542	CrAO/0.38m	Apogee E47	126
181.312 - 181.410	CrAO/0.38m	Apogee E47	47
183.288 - 183.387	CrAO/0.38m	Apogee E47	48
184.351 - 184.440	CrAO/0.38m	Apogee E47	41
202.346 - 202.490	CrAO/0.38m	Apogee E47	69
205.301 - 205.388	CrAO/0.38m	Apogee E47	42
206.342 - 206.435	CrAO/0.38m	Apogee E47	42
209.340 - 209.397	CrAO/0.38m	Apogee E47	28
212.323 - 212.391	CrAO/0.38m	Apogee E47	33
222.251 - 222.474	CrAO/0.38m	Apogee E47	111

Description of columns:
HJD 2460000+ (start-end): begin and end of observational run.
Observatory: SLO - Tatranska Lomnica, Slovakia; SLO1 - M.R. Stefanik Observatory and Planetarium, Slovakia; CrAO - Crimean astrophysical observatory, Republic of Crimea; KAZ - Kazan Federal University, Russia Federation; JAP - MITSuME telescope of Okayama Astrophysical Observatory, Japan; Bel - Association for Astronomy, Brugge, Belgium.
CCD: CCD camera type. N: number of observations.

6. Conclusion

We presented the results of multi-longitudinal 71-d photometric monitoring of the SU UMa-type dwarf nova in the period gap, V1006 Cyg in 2023. This dwarf nova showed that being a star of the SU UMa type, it can have properties of various subclasses – SS Cyg-type, Z Cam-type and IW And-type. Thus the dwarf nova V1006 Cyg shows that a division between CV subclasses may not be so sharp and deviations from standard behavior may not be so rare.

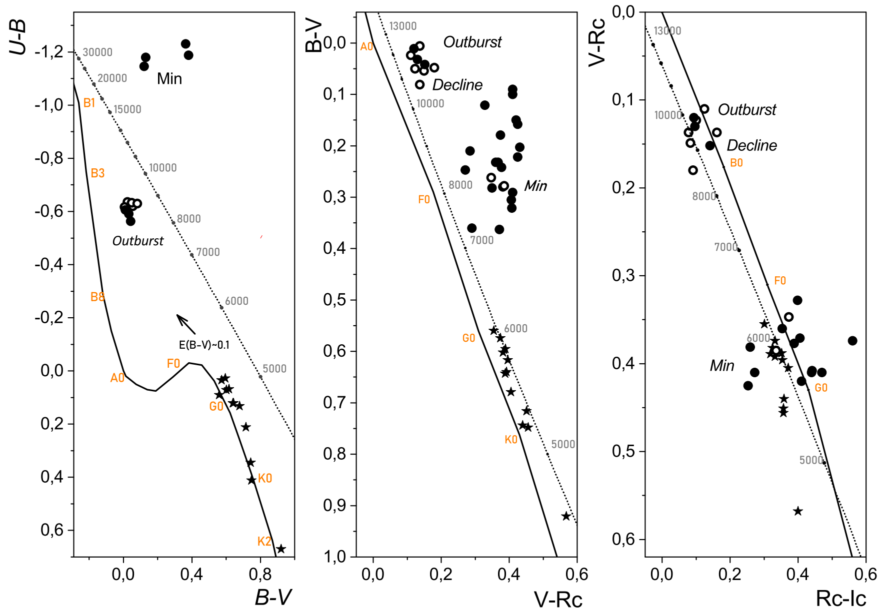

Figure 5. Two-colour diagrams. The dotted lines denote the black body sequence with a Kelvin scale marked along it. The Main sequence is designated by a solid line, the spectral classes are marked. The system state is indicated: outburst, fading or quiescence (Min). Data for the 2023 are indicated by filled circled and for the 2015 (Pavlenko et al., 2018) - by open circles. The positions of surrounding stars (shown by filled stars) are also plotted.

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