PROCEEDINGS OF SCIENCE

Dwarf Nova SS Cyg: New Photometric Data

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The results of photometric observations of the well-known dwarf nova, the SS Cyg, conducted in 2019-2021 are presented. Observations were made at various moments of the outburst cycle using several CCD cameras on two telescopes, 50 and 60-cm (~ 47,000 measurements). The search for photometric variability, carried out after taking into account the orbital variability of SS Cyg, made it possible to detect pulsations in the light curves and determine their periods and amplitudes. The analysis of the obtained values of the periods and amplitudes of pulsations allowed us to reveal the dependencies of these values on the brightness of the system at the stage of decline after outburst maximum, — there is a clear increase in the period of pulsations with a decrease in the radiation flux. With a decrease in brightness, their amplitude also increases, i.e., as SS Cyg returns to normal brightness after an outburst. At the end of April 2020 SS Cyg had an X-ray outburst. The results of optical photometry conducted in May 2020 at the end of this outburst and later in 2021 show that the behaviour of SS Cyg after the end of the X-ray outburst fits into the framework of the usual behaviour of the system at this stage of the outburst cycle.

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1. Introduction

SS Cyg is a well-known brightest dwarf nova which was first detected in the last century. It is a binary system which consist of a white dwarf as a primary component and a late-type main sequence star as a secondary. The secondary star filling its Roche lobe looses mass through the internal Lagrangian point. This matter from the secondary cannot reach the white dwarf directly because of its high angular momentum and forms an accretion disk around it. The orbital period $P \simeq 6.6^h$ was determined [1] by the study of radial velocities of SS Cyg. The outburst occurred in this system approximately every 50 day with amplitudes about $1.5 - 2.0^m$. 3 types of outbursts could be detected in SS Cyg system, — normal, long and anomalous. Its brightness could reach $\sim 8^m$ during outbursts and approximately 12^m at inactive states. The statistical characteristics of this cataclysmic variable are established very well from many observations of this star in different spectral ranges. The best review which collected the physical properties of this dwarf nova was presented by F. Giovannelli and I. Martinez-Pais [2–4]

On the light curves of dwarf novae, as in most types of accreting compact objects [5], rapid and irregular fluctuations of optical brightness are observed — so called flickering. The amplitude of flickering is often comparable to the amplitude of orbital variability. All these anomalies are associated with the presence of radiation from non-stellar components in the total radiation of the binary system.

Flickering is observed in most cataclysmic variables. The paper of [6] provides a comparative analysis of various flickering parameters for more than 100 cataclysmic variables, which is of great interest to researchers involved in determining the statistical properties of this phenomenon. Studies [7–9] are also devoted to the study of flickering. The paper [10] provides an overview of flickering studies in dwarf novae. The characteristics of individual outbursts are considered in [11, 12]. According to Baptista [14], who study dwarf nova HT Cas flickering is practically absent during the eclipse of a white dwarf, which indicates its connection with a compact object or disk around it. The physical nature of flickering has not yet been fully understand. At the moment, several different physical mechanisms have been proposed to explain it. The most studied are magnetohydrodynamic processes in the field of gaseous flow-disk interaction [5, 6], as well as instabilities in the processes of accretion of matter in the disk.

The proposed study examined the characteristics of flickering in optical and near-infrared radiation of the dwarf nova SS Cyg on the descending branches of the system's light curve in the period after maximum of the outburst, which is important for understanding the mechanisms of formation and nature of this interesting phenomenon

2. Our Observations

The new CCD observations of dwarf nova SS Cyg were made with the help of the two telescopes 50 and 60-cm at the Crimean Observational Station of Lomonosov Moscow State university (KAS) in 2019-2021. 4 CCD cameras were used as detectors, they are named further.

Apogee Aspen Sensor E2V ($13' \times 13'$, $0.38''$ per pxl, 1 pxl=13.5 μm) (1),

+ FLIPL4022 (field $7' \times 7'$, $0.20''$ per pxl, 1 pxl=7.4 mkm) (2).

+ FLI PL16803 (field $17' \times 17'$, $0.25''$ per pxl, 1 pxl=9.0 mkm) (3),

+ Apogee Alta U8300 (field 22′ × 30′, 0.54′′ per pxl, 1pxl=5.4 mkm) (4),

The accuracy of our observations was $0^m.02-0.035^m$ (for the observations on 50-cm telescope) and $0^m.01 - 0.03^m$ (for observations on 60-cm telescope)

The time interval between two consecutive measurements is Δt — 9 sec (50-cm telescope), Δt — 6.7 sec and 8 sec (60-cm telescope) for observations in June and November respectively. The comparison star which we used for our observation: BD + 424186 (GSC 03196–00785) with magnitudes $V = 9^m.80$, $B - V = 0^m.38$, $U - B = 0.^m27$ [38], $R_c = 9^m.60$ 14 observational sets were obtained on the 60-cm telescope and 9 observational sets — on the 50-cm telescope, more than 47000 measurements in V and R at all. The details of our observations one can find in Table 1 below.

Table 1: Journal of observations

Date	JD2450000+	Band	telescope	$\varphi_1 - \varphi_2$	n	$\langle m \rangle$
20.06.2019	8655.303–.542	R_c	60 cm	0.479 – 1.376	3076	9.665
21.06.2019	8656.308–.498	R_c	60 cm	0.247 – 0.958	2370	9.983
23.06.2019	8658.306–.557	R_c	60 cm	0.739 – 1.681	3201	10.276
25.06.2019	8660.341–.541	V	60 cm	0.372 – 1.122	2417	9.665
26.06.2019	8661.329–.543	V	60 cm	0.077 – 0.878	2744	11.179
27.06.2019	8662.342–.537	V	60 cm	0.874 – 1.609	2517	11.359
08.11.2019	8796.193–.347	V	60 cm	0.855 – 1.430	3331	10.954
10.11.2019	8798.215–.456	V	60 cm	0.436 – 1.341	2237	11.528
12.11.2019	8800.288–.457	V	60 cm	0.212 – 0.843	1506	11.692
18.05.2020	8988.452–.552	V	50 cm	0.150 – 0.518	843	9.794
23.05.2020	8993.430–.524	V	50 cm	0.315 – 0.657	914	10.594
31.05.2020	9001.292–.423	V	50 cm	0.001 – 0.478	934	11.355
01.09.2020	9094.232–.508	V	50 cm	0.542 – 1.580	2066	10.361
02.09.2020	9095.236–.514	V	50 cm	0.347 – 1.389	2204	10.594
02.10.2020	9125.293–.458	V	50 cm	0.068 – 0.686	1812	10.402
27.10.2020	9150.389–.507	V	60 cm	0.185 – 0.626	714	10.599
11.11.2020	9165.134–.302	V	50 cm	0.484 – 1.113	1540	11.113
19.11.2020	9173.182–.462	V	50 cm	0.151 – 0.174	2850	11.180
02.01.2021	9217.237–.269	V	50 cm	0.891 – 1.008	382	9.045
06.09.2021	9464.289–.557	V	60 cm	0.276 – 1.254	3354	11.298
07.09.2021	9465.255–.589	V	60 cm	0.799 – 2.018	4369	10.936
20.10.2021	9508.211–.474	V	60 cm	0.530 – 1.489	3351	10.920
21.10.2021	9509.179–.445	V	60 cm	0.062 – 1.033	3404	10.937
22.10.2021	9510.202–.408	V	60 cm	0.793 – 1.545	2661	11.064
26.10.2021	9514.221–.491	V	60 cm	0.455 – 1.441	3489	10.925

The date of observations is given in the first column, JD moments of the beginning and end of the observational set in the second column, the filter in the third column, the telescope in the fourth, the corresponding orbital phases (also for the beginning and end) in the fifth, the total number of

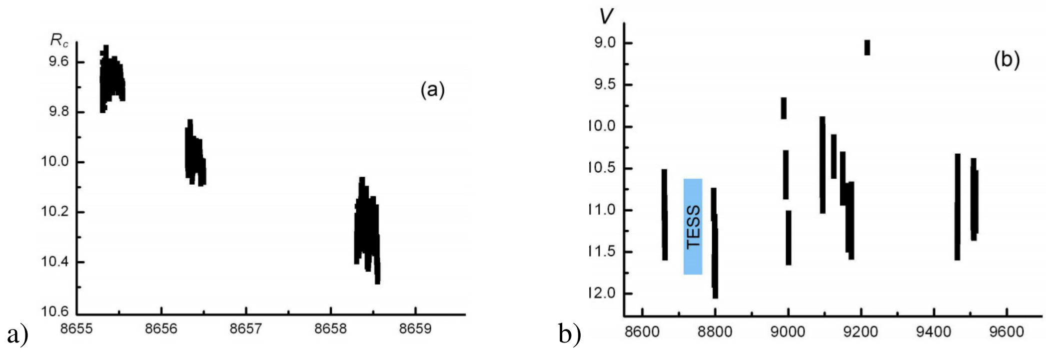

Figure 1: Our photometric observations of SS Cyg during the period 2019-2021: a). R_c filter, b). V- filter. The region of $TESS$ observations is shown by blue color

measurements obtained and the average magnitude of SS Cyg for each particular night in the last two columns.

Our observations of SS Cyg in June 2019 were done with the help of CCD №1 as a detector, later in November 2019 with CCD №2. In the following years, 2020 and 2021, CCD №4 was used as a detector for observations on both telescopes (with the exception of dates JD2459150 (CCD №2) and JD2459464 – JD2459465 (CCD №3)

Figure 1 shows the distribution of all our new observations over time. In the filter R_c on the left (a) and in filter V — on the right (b). The observations during the outbursts are clearly highlighted, when the brightness of the system reaches $m \approx 9^m$, while the minimum brightness does not exceed $11^m.5 - 12^m$. The total amplitude of the light curves is $1^m.4 - 1^m.7$ in inactive state, and drops to 0.5^m during the outbursts. Three sets in the R_c filter show a smooth drop in the average level, which is accompanied by an increase in the amplitude of the variability. Figure 1 also shows for comparison the observations of SS Cyg obtained with the Space Telescope (MAST). These data fall within the period JD2458711-2458763 on the distribution curve.

The new photometric observations of SS Cyg were performed at various stages of outburst cycle, both in the active and inactive state. To make it more clear we also present the overall outburst light curves constructed according to the AAVSO data for two seasons of our observations, June 2019 and November 2019 in Figure 2 as an example. We have plotted the same curves for all the seasons of our observations. The arrows mark the moments of our observations.

The observations themselves are shown in the following Figure 3 (some of them).

In Figure 4 the phase light curves plotted from our observations in different seasons are presented.

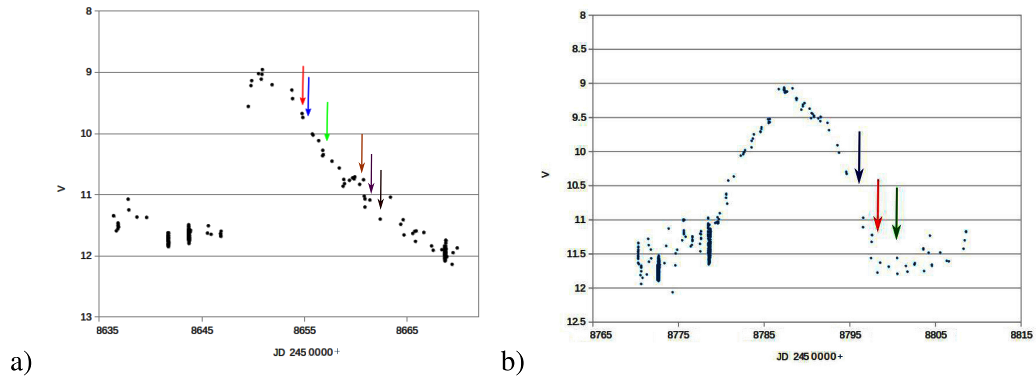

Figure 2: The overall outburst light curves in V band plotted by AAVSO data for June 2019 (a) and November 2019 (b)

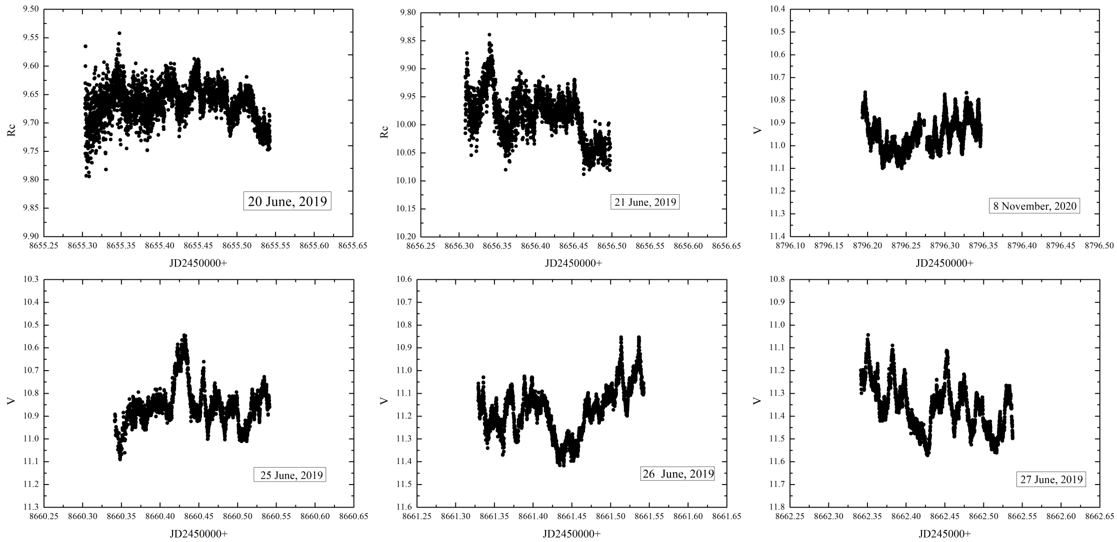

Figure 3: Some of our CCD observations of SS Cyg obtained for different seasons as an example

3. Account of Orbital Variations in Observational Light Curves

In order to search for photometric periodicities in the observational light curves of SS Cyg system, it was necessary to first take into account the orbital variability. A large massive of new observational data (more than 4700 measurements) was obtained during the period of our observations in 2019-2021. So it was possible to provide a new definition of the orbital period of SS Cyg based on all these data. This procedure was carried out using the Lafler-Kinman method [15] in the period range of 0.27-0.29 days with a step of 0.0005. It was done separately for each filter.

The periodogram obtained in this way is shown in Fig. (Figure 5). The arrow here indicates the frequency of the orbital variability obtained by data from 1983-1996 years (the corresponding P_{orb} = 0.2751302^d). It can be seen that there are no significant peaks at this frequency either in the R_c filter or in the V. The only peak with ephemeris, closest to it, and above the noise level, is clearly visible in both filters at frequencies 3.6484 (R_c) and 3.6488 (V) correspondingly

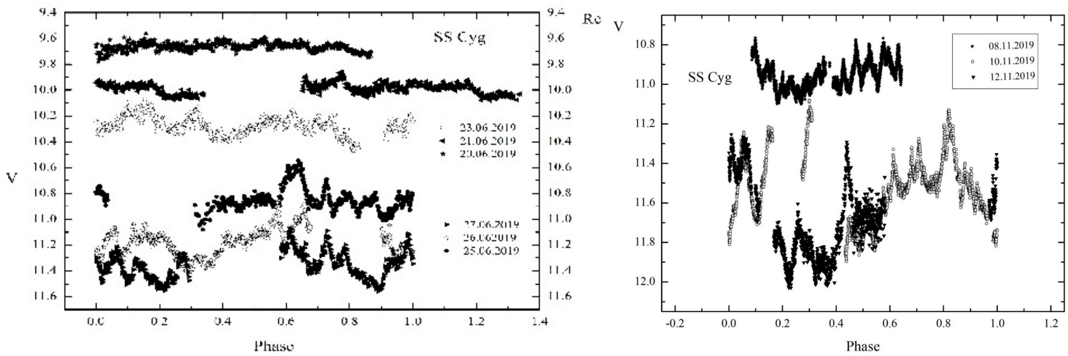

Figure 4: Phase light curves of SS Cyg for different seasons of our observations

($P_{orb}(R_c) = 0.274097^d$ and $P_{orb}(V) = 0.274066^d$). We used the average value of these periods for both filters equal to $0.27408(2)^d$, to fix the orbital variability in 2019-2021. The resulting period value $0^d.27408(2)$ differed from the previously determined more than a quarter of a century ago (1983-1996) value by approximately $\sim 0.4\%$. Due to the significant flickering presenting in the observational light curves of SS Cyg, the accuracy of this period is low, but there is no other more or less significant periods in this frequency range. However convolution of the observational data with ephemerides (see Fig. 6), despite powerful fluctuations, shows an obvious double wave over the orbital period, especially in V band.

We would like to emphasize once again that the refinement of the ephemeris is only by-product of our work, and not the main goal of this study. We undertook its refinement in order to clear the observations of orbital variability for the subsequent search for other brightness variations and study of their characteristics. So for further calculations, we took the following ephemerides for the orbital motion of the system

Min I = JD 458659.7886606+0.27408(2) E

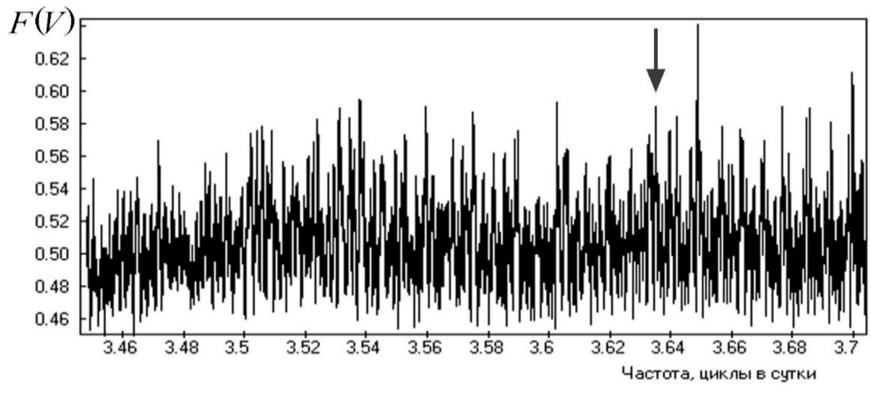

Figure 5: The power spectrum obtained from all new data in V band. The arrow shows the frequency of 3.6346 d^{-1}, corresponding to the earlier determined orbital period $P_(orb) = 0.2751302$

Convolution of SS Cyg brightness deviations from the overnight average, with ephemerides Min I=JD 2458659.7886606 + 0.27408(2) E for R_c filter (left), and filter V (right) one can see in

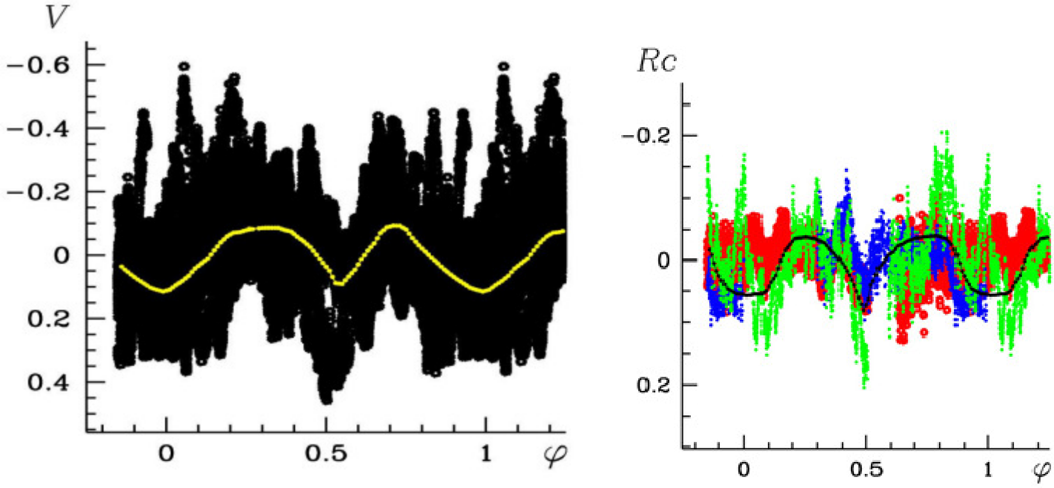

Figure 6: Convolution of the deviations of the star's brightness from the overnight average with the obtained orbital period: for V filter (left figure) and for R_c filter (right figure). The yellow and black lines indicate the mean smoothed curves plotted from all observations in this particular filter

Figure 6. The black and yellow lines are represent the average smoothed deviation curves plotted from the combined data. At each point, 300–600 observations were averaged, depending on the number of points in the 0.01 phase range. In the future we used these mean curves to exclude orbital variability from our observational data and further search for photometric variability (by deviations of the observational light curves from the mean curves).

4. Detection of Pulsations

The analysis of the data obtained after taking into account the orbital variability and other trends associated with changes in the parameters of the system overnight showed the presence of cyclic fluctuations in brightness, usually up to $\sim (4-10)$ during the orbital cycle or $flickering$. The periods and amplitudes of the detected pulsations were determined for each date of our observations. The periods were determined with the help of Lafler-Kinman method [15]. Here we present a part of this table 2 containing obtained characteristics for a few nights from different seasons as an example. The first column of this Table shows the date of observation (+JD2450000.0), the period of pulsation for this night is given in the 2nd column, pulsation amplitudes are in the 3rd, filter in the 4th. In order to understand what stage SS Cyg in, the 5th column shows the average brightness of the system at that particular night.

The obtained values of the periods and amplitudes of these pulsations for the stage of decline after outburst maximum (most of our measurements were taken when the system was at this stage) demonstrated the obvious dependence on the average brightness of the system: with increasing luminosity of the system, both these values decreased linearly. Thus, with the brightness of the system $m \sim 9$, the characteristic flickering time and its amplitude are $P \sim 0.01^d$ and $A \sim 0.1^m$ respectively; with a decrease in the SS Cyg brightness to $m \sim 12^m$, they are already equal to

$0^d.06 - 0^d.07$ and $0^m.3 - 0^m.5$. The identified dependencies are shown in Figure 7 below. However such a dependence is not observed for data in a quite state.

Table 2: Characteristics of pulsations

JD2450000.0 +	Period, day	Amplitude, mag	filter	Average magnitude
Descending branch of the outburst in June 2019				
8656	0.037(2)	0.12(4)	*Rc*	$9^m.80$
8658	0.040(2)	0.24(6)	*Rc*	$10^m.280$
8662	0.056(3)	0.38(7)	*V*	$11^m.360$
Descending branch of the outburst in May 2020				
8988	0.027(2)	0.12(3)	*V*	$9^m.80$
8993	0.034(3)	0.35(7)	*V*	$10^m.59$
9001	0.064(3)	0.47(1)	*V*	$11^m.360$
Minimum between two outbursts				
9165	0.037(3)	0.55(10)	*V*	$11^m.11$
9173	0.057(3)	0.45(12)	*V*	$11^m.18$
9508	0.057(5)	0.35(10)	*V*	$10^m.92$

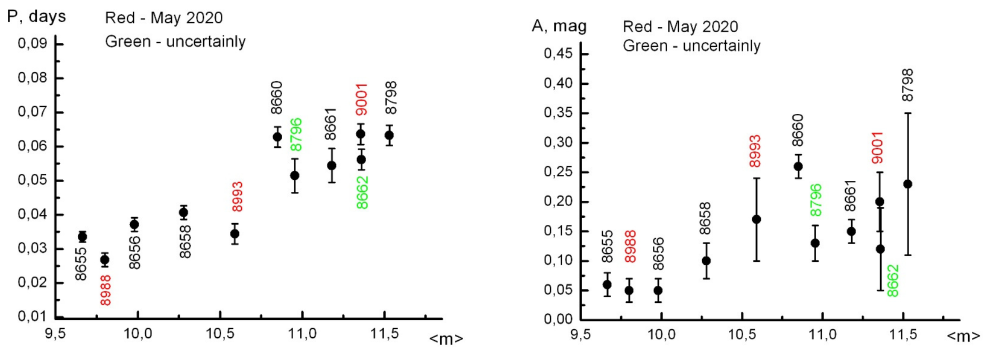

Figure 7: The dependencies of the pulsation period and amplitudes on the brightness of the system obtained for the stage of decline after the outburst maximum (observations in May 2020 at the end of the X-ray outburst are shown by red)

Purely geometric considerations show that the source of the flickering is located in the region of interaction of the gas flow with the near-disk halo, only this region in the system with the parameters q, i, R_d [19] can be closed at large disk radii and is clearly visible at all other phases of the orbit from this system. For a better understanding, we provide a schematic image of the system below (see Figure 8).

The flickering source must satisfy the following conditions, firstly, visibility at all orbital phases and, secondly, sometimes (apparently with a larger radius of the disk) is eclipsed during the lower conjunction of red dwarf ($\sim 0.9 - 1.1$). Let's consider where it can be located,

So, it cannot be the inner part of the disk, because, although it is visible during the entire orbital cycle, it does not meet the second condition.

This cannot be a hot spot, because although in phases ~ 0 it may well be eclipsed with a large radius of the disk, but in phases ~ 0.4-0.6 the spot is not visible to the observer (it is located on the side surface of the disk, to the right of the base of the hotline, (shown in brown in the Figure 8).

This cannot be the area near the inner Lagrange point L1, because it is also not eclipsed by the edge of the disk at any of its radii for the obtained system parameters (q = 1.5, i = 52.5, $R_d = 0.42; 0.64; 0.75$), which is also clearly shown in Fig. The only structure that can be eclipsed at phases ~ $(0.9 - 1.1)$, but will be visible in the remaining orbital phases of the cycle, including phases 0.4–0.6, is gaseous flow.

Our assumption about the source of flickering in the system is only one of the possible explanations for the observed pulsations. More reliable solutions to this problem can be obtained from theoretical calculations of the flow of matter in cataclysmic variables.

To find out the cause of the flickering, it is also necessary to continue long-term high-speed observations of this system covering all stages of the outburst cycle.

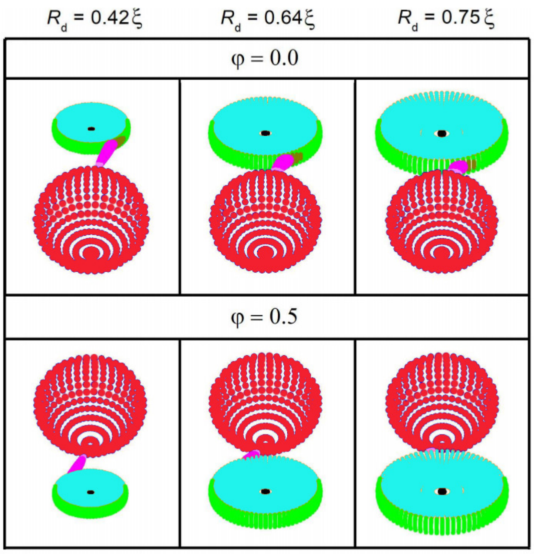

Figure 8: Schematic images of the SS Cyg system

5. Summary of Results

- Pulsations were detected in the light curves of SS Cyg obtained from observations in 2019-2021 years. The periods and amplitudes of these pulsations were determined.

- The analysis of pulsations periods and amplitudes allowed us to reveal their dependence on the luminosity of the system at the stage of the brightness decline after the maximum (most of our observations were obtained at this particular stage of the outburst) , — there is a clear increase in the period of pulsations with a decrease in the radiation flux. With a decrease in brightness, their amplitude also increases, i.e., as SS Cyg returns to its normal brightness after an outburst.

- Values obtained for observations in May 2020 fit well on the revealed dependence, and the behaviour of SS Cyg at the end of the X-ray outburst is typical for the system at this stage of the outburst cycle. The average value of the pulsation period is approximately $0^d.06 - 0^d.065$.
- Such a dependence is not observed at the stage of minimum light.
- It was possible to determine the colours of SS Cyg for one particular night May 18, 2020 (JD 2458988.4558 - 2458988.4785). They are: $B = 9^m.804 \pm 0.010$, $V = 9^m.827 \pm 0.009$, $R_c = 9^m.664 \pm 0.009$, $B - V = -0^m.023 \pm 0.005$, $V - R_c = 0^m.163 \pm 0.005$

The detailed results of our study will be published at Astronomy Reports in 2024.

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References

[1] A.H. Joy, Astrophys. J. **124**, 317 (1956).

[2] F. Giovannelli, I.G.Martinez-Pais, Space Science Review **56**, 313 (1991).

[3] I.G. Martinez-Pais, F. Giovannelli, C. Rossi, S. Gaudenzi Astron. Astrophys. **291**, 455 (1994).

[4] I.G. Martinez-Pais, F. Giovannelli, C. Rossi, S. Gaudenzi Astron. Astrophys. **308**, 833 (1996).

[5] S. Scaringi, arXiv:1311.6814 [astro-ph.GA] (2013).

[6] A. Bruch, Monthly Not. Roy. Astron. Soc. 503(1), 953 (2021).

[7] J.I. Gonzalez Hernandez, R. Rebolo, and J. Casares, Monthly Not. Roy. Astron. Soc. **438**, L21 2014,

[8] D.M. Russell, T. Shahbaz, F. Lewis, and E. Gallo, Monthly Not. Roy. Astron. Soc. **463**, 2680, 2016

[9] A. Bruch, Astron. and Astrophys. **359**, 998 (2000).

[10] A. Bortoletto and R. Baptista, Revista Mexicana Astron. Astrof. **20**, 247 (2004)

[11] T. Shahbaz, R.I. Hynes, P.A. Charles, C. Zurita, J. Casares, C.A. Haswell, S. Araujo-Betancor, and C. Powell, Monthly Not. Roy. Astron. Soc. **354**, 31 (2004).

[12] R.I. Hynes, P.A. Charles, J. Casares, C.A. Haswell, C. Zurita, and T. Shahbaz, Monthly Not.Roy. Astron. Soc. **340**, 447 (2003).

[13] D.M. Russell and R.P. Fender, Monthly Not. Roy. Astron. Soc. **387**, 713 (2008).

[14] R. Baptista, B. Borges, V. Kolokotronis, O. Giannakis, and C.J. Papadimitriou, arXiv:1105.1382 [astro-ph.SR] (2011).

[15] D.M. Himmelblau, *Applied Nonlinear Programming*. McGraw-Hill, 1972

[16] I. Voloshina Soviet Astronomy Letters, **12**, Mar.-Apr. 1986, p. 89–93.

[17] I. Voloshina & V. Luytij, Astron. Rep. **37** (1), 34 (1993).

[18] A. Bruch, Acta Astronomica **40**, 369 (1990).

[19] I. Voloshina & T. Khruzina Astron. Rep. **77**(2), 109 (2000).

[20] G. Grant and H.A. Abt, Astrophys. J. **129**, 320 (1959).

[21] T.S.Khruzina (model) Astron. Rep., **55** (5): 425-436, May 2011

[22] T.S. Khruzina, I.B.Voloshina, V. Metlov Astron. Rep., **93**(11), 942 (2016).

[23] T.S. Khruzina, I.B. Voloshina, S. Qian, V.G. Metlov, Astron. Rep., **62**, Issue 1, pp.31-49 (2018)

[24] T.S. Khruzina, I.B. Voloshina, S. Qian, M. Wolf, V.G. Metlov Astron. Rep., **63**, Issue 7, pp.571-594 (2019).