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Confirmation of the New Evolutionary Status of UU Cas

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Abstract—A new spectral study of the close binary system (CBS) UU Cas with massive components was carried out, based on spectra obtained on the echelle spectrometer of the 1.2-m telescope of Kourovka Astronomical Observatory of UFU from 2017 to 2022. The results of this study confirm the new evolutionary status of UU Cas, previously determined by the author based on spectrophotometry of this system in 2017 and confirmed in a number of works by other researchers, according to which the system is in the final stage of the mass exchange process, and not at its beginning, as previously thought. Its components are not very massive, and the value of their mass ratio is the opposite of what was previously determined from photometry results. The values of the half-amplitudes of the radial velocities $K_1 = 195.6$ km/s, $K_2 = 106.5$ km/s and the masses of both components $M_1 = 9.6\ M_\odot$, $M_2 = 17.6\ M_\odot$ obtained on a much more extensive observational material, for the orbital inclination angle $i = 74.5°$, given recently in the literature, as well as the orbital radius $A = 54\ R_\odot$ of this close binary system are comparable with the values previously found by the author. The article is based on a talk presented at the astrophysical memorial seminar "Novelties in Understanding the Evolution of Binary Stars," dedicated to the 90th anniversary of Professor M.A. Svechnikov.

Keywords: eclipsing variable stars, close binary systems, spectroscopic binary, radial velocity

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1. INTRODUCTION

For almost 80 years, the eclipsing variable UU Cas ($V = 10.4^m$–10.8^m, $P = 8.51929^d$) was known as a close binary system (CBS) with very massive components of the order of magnitude 30 $M_\odot$ or more. The conclusion was made on the basis of the first and, until 2009, the only spectral study of UU Cas, carried out by Sanford [1] back in the 1930s of the last century. In the obtained photographic spectra, he detected lines of only one component and determined its spectral type as B1. Considering the half-amplitude of the constructed radial velocity curve, $K_1 = 161$ km/s, Sanford estimated the mass of the visible component to be within 30–100 $M_\odot$. The first value corresponded to the case of equal masses of the components, the second—to half the mass of the secondary component $q = M_2/M_1 = 0.5$. The case of a smaller mass of the secondary component was considered by Sanford as more realistic, because its lines were not visible in the spectrum. Based on these data, the UU Cas system has long been considered one of the most massive known close binaries.

This conclusion was confirmed by Parenago and Kukarkin [2] based on photographic photometry data. Having obtained the ratio of the luminosities of the components from the solution of the light curve, they, using the "Mass—Luminosity" relationship, estimated the ratio of the masses of the components ($q = 0.68$), as well as the values of their masses themselves: $M_1 = 58\ M_\odot$, $M_2 = 40\ M_\odot$ [2]. These results did not contradict the conclusions of Sanford [1] about the large masses of the components of this CBS. More accurate modern light curves of UU Cas obtained by Kumsiashvili [3] and Polushina [4] using photoelectron radiation detectors showed significant (up to 0.08^m) brightness deviations from the average values. This was explained by the presence of a gas component in the system (common shell, gas jets), formed as a result of the more massive component filling its Roche cavity. The estimates of the masses of the components in the interval 23–35 $M_\odot$ obtained in the process of solving light curves using the synthesis method [5] and the classical Russell-Merill method [4] also did not contradict the previously made conclusions that UU Cas is a massive CBS. Thus, based on the results of photometric observations, it was assumed that the UU Cas system is at the initial stage of the first mass exchange. The brighter and more massive component fills its Roche lobe and supplies matter to the second less massive and less bright component.

In 2008, using the 2-m telescope of the Bulgarian National Observatory, Markov et al. [6, 7] obtained a series of UU Cas spectra in two spectral intervals. In

Table 1. Component masses and semimajor axis of the UU Cas orbit

No.	Reference	i, deg	$M_1/M_\odot$	$M_2/M_\odot$	$q = M_2/M_1$	$A/R_\odot$
1	[4]	69	34.5 ± 1.5	25.7 ± 0.6	0.75 ± 0.3	69.0 ± 0.7
2	[5]	69	26.0	23.4	0.8	65.0
3	[10]	69	9.5 ± 2.1	17.7 ± 2.3	1.85 ± 0.02	52.7 ± 0.5
4	[12]	74.5	9.0 ± 0.2	17.4 ± 0.3	1.93	52.2 ± 0.3

Data are presented from the works of Polushina [4], Antokhina and Kumsiashvili [5], Gorda [10], Minnikent et al. [12].

these spectra, the H_α line was observed in strong emission. The authors noted a change in the line shape with the photometric phase, which indicated the presence of gas in the system.

Using the displacements of the lines of neutral helium and nitrogen, Markov et al. [6, 7] constructed a radial velocity curve for the main component, similar to the Sanford curve, but with a half-amplitude 25% larger. Attempts to construct the radial velocity curve of the second component from the lines of neutral helium were unsuccessful due to the insufficient number of spectra obtained at phases where the duality of the spectral lines of helium was clearly manifested. Analyzing the change in the shape of the H_α emission line profile, the authors suggested that the secondary component of the system, poorly manifested in the spectrum, is surrounded by a thick accretion disk, which significantly screens the radiation flux from it. A model of the UU Cas system with an accretion disk around the massive component was presented in the work of Djurašević et al. [8].

In the period from January to April 2017, the author obtained a number of spectra of UU Cas using the high-resolution fiber-optic echelle spectrometer of the 1.2-m telescope of the Kourovka Astronomical Observatory of the Ural Federal University [9].

As in the spectra of Markov et al. [6, 7], a significant phase-varying emission was observed in the H_α line, while the neutral helium lines had a clearly defined two-component structure. The author managed to separate almost all He I line blends into components and construct radial velocity curves, for the first time for the secondary (in photometric terms) component. The resulting value of the ratio of the masses of the less massive component to the more massive one, $Q = M_1/M_2 = K_2/K_1 = 0.54$, turned out to be significantly less than the estimates found from the solutions of the light curves $q = M_2/M_1 = 0.75–0.8$ [4, 5]. In addition, the mass ratio of UU Cas components obtained from spectral data ($M_1 < M_2$) turned out to be the opposite of what was determined from photometry ($M_1 > M_2$). In addition, the values of the masses of the components themselves, found from the spectral data, turned out to be significantly less than their estimates previously determined from the results of photometry (see the first three lines of Table 1). The results of this spectral study are presented in more detail in the work of Gorda [10].

Based on the results obtained by the author, it was concluded that in the UU Cas system the transfer of matter occurs from a component that has become less massive, filling its Roche lobe, to a more massive, but photometrically less bright component. This suggests that the process of mass exchange in the UU Cas CBS has been going on for quite a long time and the system is probably in its final stage. The lower brightness of the more massive component, as noted in the works of Markov et al. [6, 7] and Djurašević et al. [8], is associated with the presence of an optically dense gas disk surrounding this component.

The study of the structure of the gas component in the UU Cas system by the Doppler tomography method based on spectral data obtained by the author, and presented in the work of Kononov, Gorda and Parfenov [11], showed the presence of all structures inherent in the process of matter transfer between the components. Namely, the presence of a gas flow from a brighter component through the point L_1 was discovered, as well as the presence of a gas component surrounding a more massive, but less bright to the observer, component.

The new mass ratio of UU Cas components obtained by the author was used in the work of Minnikent et al. [12] in a photometric study of UU Cas. In this work, the authors used photometric data from a number of reviews, as well as from the above-mentioned works by Polushina [4] and Antokhina and Kumsiashvili [5].

When determining the parameters of the UU Cas system based on the combined light curve data, the authors used the disk model of Djurašević [9]. The masses of the components and the distance between them that they found, in contrast to previous photometric studies of UU Cas, turned out to be close to the spectral determinations of Gorda [10] (see the last line of Table 1). The general characteristics of the system, both in terms of evolutionary status and in terms of gas-dynamic structure, presented in this work, completely coincide with the conclusions given in the works of the author or carried out with his participation [10, 11].

Quite recently, almost the same group of coauthors, led by Peter Hadrava, conducted a spectral study of the UU Cas system using all currently known spectral data of this star [13]. In particular, all the spectra obtained at that time by the author were used, on the basis of which the results presented above had already been obtained.

Separation of the spectral regions of the close binary UU Cas, which contained blends of spectral lines, into individual components was performed using the KOREL code in the Fourier domain [14]. The profile of each absorption line was divided into three components. These are photospheric absorptions of two components and absorption formed in the optically thin region of the gas component (disk). The value of the component mass ratio q_{sp}, found from all known UU Cas spectra, as in the author's work [10], turned out to be the opposite of the determinations previously obtained exclusively from photometric data (light curves). The average value $q_{sp} = M_2/M_1 = 2.54 \pm 0.68$ turned out to be even greater than that found in the author's work [10] (see third row of Table 1).

Spectral observations of UU Cas at the Kourovka Observatory were continued. Over the past 5 years, a large number of new spectra have been obtained. Therefore, it was of some interest to obtain new, in comparison with the 2017 data, values of the parameters of this CBS, using similar methods for processing the observational material. In order to simplify the comparison of the newly obtained data with the results presented in previously published works, we will consider the brighter, but less massive component (M_1) to be the main component, and the more massive component (M_2) to be the secondary component, respectively.

2. NEW SPECTRAL STUDY OF UU Cas AT KOUROVKA OBSERVATORY

2.1. Observations and Data Processing

All UU Cas spectra were obtained by the author in the period from January 2017 to April 2022 on a high-resolution fiber-optic echelle spectrometer R = 15000 [15, 16] of the alt-azimuth telescope (D = 1.21 m, F = 12.0 m) of the Kourovka Astronomical Observatory of the Ural Federal University [9]. An ANDOR DZ936N-BEX2-DD (2048×2048, 13.5 μm) CCD camera was used as a light receiving device in the spectrometer, with the CCD chip cooled to a temperature of −85°C.

Over the entire observation period, 47 UU Cas spectra were obtained, fairly uniformly distributed over the photometric phase range. The spectrograms contained 60 overlapping orders, covering the spectral interval 4100–7500 Å. Pre-processing of the newly obtained 29 spectra was carried out according to the scheme described in detail in Gorda's work [10].

In all UU Cas spectra, the strongest were the He I lines, as well as the lines of singly ionized nitrogen N II in the λ5680 Å region. All N II lines had a single-component structure and, as was first shown by Markov et al. [7], belonged to the brighter UU Cas component. In contrast to the lines of ionized nitrogen, the line profiles of neutral helium, especially in the spectra obtained at phases close to quadrature, showed a clear two-component structure. Moreover, one of the components was always noticeably deeper than the other. For the study, we selected the profiles of the three strongest lines in the spectra, He I 5875, He I 6678, and He I 7065. The profiles of the "bluer" helium lines were less deep and significantly noisy, so they were not used in the work.

The separation of the He I spectral line profiles in the newly obtained spectra was carried out by the Gaussian approximation method. Moreover, considering that the helium line profiles may contain an emission component due to the presence of a gas component in the UU Cas system and the relatively low excitation potential of helium atoms, the approximation of the line profiles, as in the author's previous work [10], was carried out using three Gaussians.

After dividing the He I line profiles into components, their radial velocities were calculated and heliocentric additives were considered. Next, the average radial velocities for a given date were calculated. For the more massive, now main component, the values obtained from the three helium lines were averaged. For the less massive, respectively, secondary component, the radial velocities obtained from three helium lines and four lines of singly ionized nitrogen were averaged. The average radial velocities obtained from all spectra, the corresponding photometric phases and observation times are given in Table 2.

The photometric phase values were calculated using the formula below, which is used throughout almost the entire period of the UU Cas study, since a change in its period has not yet been detected:

$$\mathrm{JD}_{\odot} = 2445722.10557 + 8.51929^d E.$$

2.2. New Radial Velocity Curves for UU Cas

The calculated radial velocities were approximated by the sine function, since it follows from the photometric and previously obtained spectral data that the orbits of the components are circular. When constructing radial velocity curves using the nonlinear least squares method, the values of V_r for both components at phases from 0.9 to 0.1 and from 0.4 to 0.6 were not used, because they were determined with a large degree of uncertainty (see data in Table 2). The approximation results are illustrated in Fig. 1, and the values of the corresponding coefficients are given in Table 3. The last column of this table contains the values of the root-mean-square errors in the scatter of the

Table 2. Moments of observation of spectra, photometric phases and radial velocities of the UU Cas components

Date	HJD 2450000+	Phase	$V_r(M_2)$, km/s	±σ, km/s	$V_r(M_1)$, km/s	±σ, km/s
25.01.2017	7779.2327	0.2725	66.1	5.3	−251.4	3.5
09.03.2017	7822.1542	0.3119	78.4	8.1	−243.2	3.9
14.03.2017	7827.1870	0.9016	−101.9	4.5	65.6	2.9
14.03.2017	7827.5055	0.9400	−83.2	6.0	32.0	1.7
16.03.2017	7829.1793	0.1362	27.5	4.3	−206.4	2.8
16.03.2017	7829.4956	0.1734	57.9	6.4	−214.3	3.1
19.03.2017	7832.1715	0.4888	−25.2	13.6	−95.4	5.1
19.03.2017	7832.4737	0.5231	−67.6	12.6	−43.6	3.5
21.03.2017	7834.1746	0.7228	−137.8	4.6	118.8	4.3
21.03.2017	7834.5055	0.7617	−135.3	3.4	129.9	2.9
22.03.2017	7835.1760	0.8404	−111.4	5.4	100.9	2.6
22.03.2017	7835.4786	0.8756	−114.7	7.1	78.9	2.0
06.04.2017	7850.4891	0.6378	−102.7	10.5	87.6	8.5
11.04.2017	7855.4478	0.2200	65.6	3.4	−234.9	2.9
27.07.2017	7962.3184	0.7644	−141.1	4.2	141.8	3.1
11.10.2017	8038.1650	0.6657	−102.5	7.6	97.2	5.5
05.01.2018	8124.2657	0.7738	−128.0	5.5	146.2	3.7
06.01.2018	8125.2304	0.8797	−121.2	9.9	89.9	5.8
08.02.2018	8125.2304	0.7608	−139.6	4.7	141.5	3.3
12.01.2018	8131.1649	0.5838	−100.0	9.3	41.7	6.5
08.02.2018	8158.2315	0.7608	−139.6	4.9	141.5	5.3
09.02.2018	8159.1406	0.8677	−117.9	6.1	120.4	4.9
16.02.2018	8166.1603	0.6909	−121.4	5.8	120.3	2.9
19.03.2018	8197.1714	0.3332	73.8	8.5	−206.7	4.0
12.04.2018	8221.4272	0.1788	56.1	10.0	−207.8	7.8
06.02.2019	8521.2142	0.3680	68.0	7.5	−213.7	3.2
16.03.2019	8559.1611	0.8220	−144.8	8.5	111.4	5.5
01.04.2019	8575.4940	0.7395	−156.0	4.5	134.1	2.1
05.04.2019	8579.4733	0.2066	41.9	5.6	−226.1	4.5
06.04.2019	8580.4816	0.3249	67.5	3.6	−245.0	2.3
14.04.2019	8588.4581	0.2612	46.0	2.2	−256.7	2.7
19.10.2019	8776.5064	0.3344	68.2	4.5	−239.5	1.5
14.12.2019	8832.3328	0.8873	−119.2	11.7	53.5	6.6
29.12.2019	8847.2779	0.6416	−135.4	8.4	80.2	5.7
02.10.2020	9125.2068	0.2650	35.0	3.9	−260.0	2.8
12.10.2020	9135.1654	0.4340	19.0	12.1	−155.5	7.6
10.12.2020	9194.2611	0.3706	56.6	7.3	−210.8	3.5
19.12.2020	9203.3787	0.4409	6.1	10.5	−142.8	7.8
18.01.2021	9233.2613	0.9486	−89.3	11.4	22.6	9.7
01.03.2021	9275.1689	0.8678	−135.8	8.5	76.0	5.3
13.03.2021	9287.1737	0.2773	54.4	3.5	−259.7	2.7
30.03.2021	9304.4472	0.3045	70.1	4.8	−252.8	3.2
12.04.2021	9317.4111	0.8262	−140.7	9.2	107.3	6.2
16.04.2021	9321.4224	0.2971	59.0	4.8	−243.0	3.4
02.11.2021	9521.3907	0.7698	−154.3	5.4	135.7	2.6
12.01.2022	9592.2739	0.0897	28.2	9.5	−167.4	7.6
22.04.2022	9692.4027	0.8429	−133.2	6.2	117.5	3.3

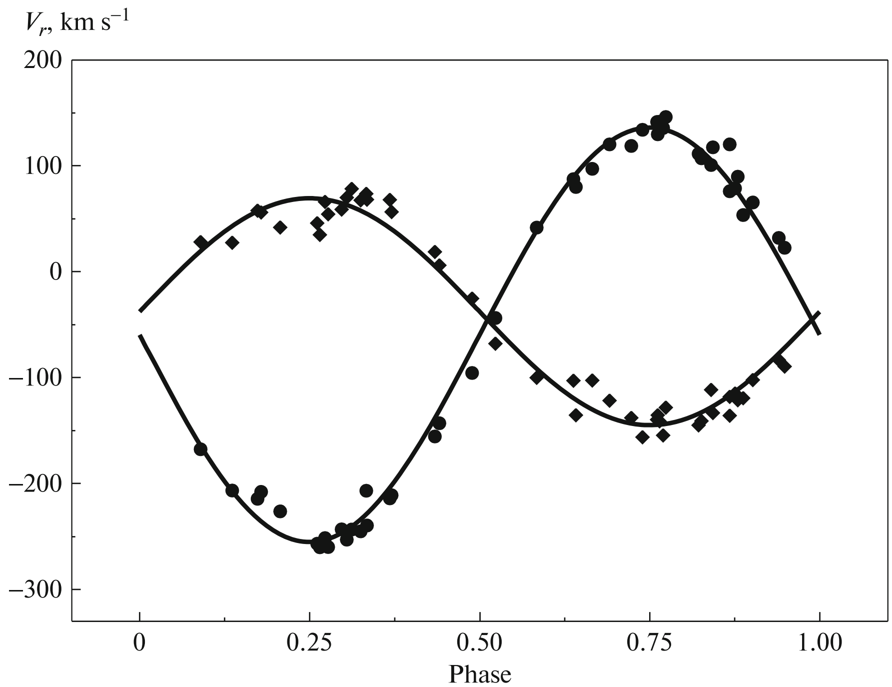

Fig. 1. Radial velocity curves of the UU Cas components (solid lines). The dots correspond to the radial velocities of the less massive component (M_1), and the diamonds correspond to the radial velocities of the more massive component (M_2).

obtained values of the radial velocities of the components relative to the corresponding radial velocity curves.

The mass values accurate to the $\sin^3(i)$ factor, as well as the projections of the semi-major axes of the orbits of the components are given in Table 4, and the values of the masses of the components and the size of the semi-axis of the mutual orbit for two inclination angles $i = 69°$ [3, 4] and $i = 74.5°$ [12] are in Table 5.

Table 3. Values of the coefficients of the radial velocity curves of the UU Cas components

V_0, km/s	K_1, km/s	K_2, km/s	σ, km/s
−59.6 ± 2.0	−195.6 ± 2.3	—	±13.0
−37.7 ± 2.2	—	106.5 ± 2.8	±14.0

The last column shows the values of the root-mean-square errors in the scatter of the obtained values of the radial velocities of the components relative to the corresponding radial velocity curves.

Table 4. Values of $M\sin^3(i)$ and projections of the semi-major axes of the orbits of the UU Cas components

Parameter	Value
$M_1 \sin^3(i), M_\odot$	8.6 ± 2.3
$M_2 \sin^3(i), M_\odot$	15.8 ± 2.3
$a_1 \sin(i), R_\odot$	32.7 ± 0.5
$a_2 \sin(i), R_\odot$	17.8 ± 0.4
$q = K_1/K_2$	1.84 ± 0.02

3. CONCLUSIONS

Thus, based on the use of the entire volume of spectral data, including 29 new spectra obtained within five years after the first spectral study by the author [10] of an eclipsing variable star UU Cas with massive components of the early spectral type on the echelle spectrometer of the 1.2-m telescope of Kourovka Observatory of the Ural Federal University, the values of the masses of the components were obtained, which are in good agreement with the results of the previous determination [10] (see Table 1 and Table 5). In the concept of a model of this CBS proposed by Djurašević et al. [8] and consisting of a component filling its Roche lobe and a smaller component surrounded by an optically thick disk formed due to the flow of matter from a neighbor, the method used by the author for separating spectral blends of the lines of UU Cas into components by approximating them with

Table 5. Component masses and semi-major axis of the UU Cas orbit

i, deg	$M_1/M_\odot$	$M_2/M_\odot$	$A/R_\odot$
74.5	9.6 ± 2.3	17.6 ± 2.3	52.4 ± 0.5
69.0	10.6 ± 2.3	19.4 ± 2.3	54.1 ± 0.5

three Gaussians, representing two absorption and one emission (gas) components, is quite adequate, allowing one to obtain fairly correct values of the system parameters. However, it should be noted that the spectral line profile of a more massive component surrounded by a gas disk may contain an absorption component from the heated, optically thin part of the disk. This can lead to a shift of the center of the spectral line towards an increase in the absolute value of the radial velocity due to the higher rotation speed of the disk compared to the speed of the center of mass of the component, which will lead to an underestimation of its mass. This probably explains the higher value of the mass ratio of the UU Cas components obtained in the work of Hadrava et al. [13] when decomposing the spectral line profiles into components using his method [14], which considers the absorption component of the disk.

Apparently, the value V_0 for the less massive component should be taken as the value for the velocity of the UU Cas system relative to the Sun (see the first row in the first column of Table 3), because the influence of the gas component present in the system on its radiation is minimal or completely absent.

Thus, based on the new data obtained, the conclusion about the new evolutionary status of UU Cas, made by the author in [10] and confirmed in a number of works of other researchers mentioned above, was confirmed in this study.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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