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Photometric and Spectroscopic Study of Nova Cassiopeiae 1995 (V723 Cas)

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Abstract—We report an 11-year long series of $UBVRI$ observations and the results of our monitoring of the classical slow nova V723 Cas. We analyze the spectra of this star taken using the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences with a spectral resolution of 3.5–8.5 Å during the nebular stage and at the supersoft X-ray source phase (SSS). This system has a large orbital inclination and its orbital period is equal to 0.693265 days. The orbital period increases. We found low-amplitude light variations with the orbital period during the early stages of the outburst and even at the pre-maximum stage. The orbital light curve at the nebular stage is asymmetric and gradually increases its amplitude up to V=2^m in 2006. The asymmetry of the light curve of V723 Cas can be explained by the reflection effect, eclipse of the extended accretion disk, and high rate of mass transfer in the system. The light curve of V723 Cas has developed a plateau due to the SSS phase. In the spectrum of V723 Cas the transition to the SSS phase shows up in an order-of-magnitude increase of the flux of the [Fe X] λ 6374 Å emission, which forms in the expanding envelope. In addition, narrow emission lines λ 6466.4 Å (O V) and λ 6500.5 Å (Fe XVII) also emerged in the spectrum.

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1. INTRODUCTION

The classical nova V723 Cas ($1^h\,05^m\,05\overset{s}{.}35$, $+54°00'40\overset{''}{.}1$, 2000) was discovered by M. Yamamoto [1] on August 24, 1995, when its magnitude was $V = 9\overset{m}{.}2$. Before its outburst, the nova was a faint star, which, according to the Palomar atlas, had the red and blue magnitudes equal to $R = 17\overset{m}{.}5$ and $B = 19\overset{m}{.}0$, respectively [2]. The star reached its maximum light on December 17, 1995 (JD 2450069) during the peak of a short outburst: $U = 7\overset{m}{.}61$, $B = 7\overset{m}{.}59$, $V = 7\overset{m}{.}09$, and $R = 6\overset{m}{.}59$. During the declining part of its light curve, the nova exhibited outbursts and outburst episodes with a duration of up to 100 days, which consisted of a series of chaotic outbursts with amplitudes of up to 2^m. If the peak of the most powerful outburst is considered to represent the maximum light of the star, one can find the three-magnitude drop time in the B and V bands to be equal to $t_3 = 173 \pm 5$ and $t_3 = 189 \pm 5$ days, respectively [3]. The inferred two-magnitude drop time, t_2, is very uncertain, because of the large-amplitude light variations during outbursts. The t_3 time scale does not reflect the parameters of exponential light decay and evolution of the spectrum. We excluded outbursts and smoothed rapid variations of the light curve to find the following parameters for the V-band light curve: $t_2 = 340^d$ and $t_3 = 515^d$. The accuracy of these parameters are of about several tens of days. Such decline rates allow the star to be classified as the slowest nova.

The outburst of V723 Cas was observed throughout a wide range of the electromagnetic spectrum: at radio and optical wavelengths and also at X-rays.

The star V723 Cas is distinguished by its very long (three months) pre-maximum stage [4]. After Gertz [5], this outburst stage came to be known as “optically thick fireball”. The binary proved to be located inside a fireball and it was surrounded by the common expanding photosphere. By the energy distribution in the continuum the optical spectra of the nova during this stage resembled that of an intermediate F-type supergiant with weak emission lines [6]. The star exhibited H_α emission of intermediate strength. The higher terms of the Balmer series appeared as pure absorptions. Other weak emission lines belonged to He I and Fe II, leading the researchers to classify V723 Cas as an Fe II class nova. From October through November, 1995 emission lines gradually decayed, whereas absorption components became stronger. The velocity of the emission components was rather stable, at −57.7 km/s [4]. Note that this is approximately equal to the velocity of the binary directed toward the observer. The velocity of absorption components decreased from −220 km/s at the early stage down to −150 km/s in late December, 1995, so that, systemic velocity taken into account, the maximum envelope expansion velocity in the pre-maximum stage amounted to only 160 km/s. Only one other nova — RR Pic — is known to have had lower expansion velocity during the pre-maximum stage. Photometry of V723 Cas during the pre-maximum stage showed slow and nonmonotonic brightening within 1^m, and this fact allows us to hope that photometric methods would be capable to provide information about the behavior of this binary system inside the common photosphere.

During the peak of a major outburst on December 17, 1995, which determined the main maximum, the blue spectrum contained absorption lines exclusively and resembled that of the F0Ia-type star HR 382 [4]. After this outburst, an extended rarefied atmosphere formed as a result of a mass ejection. This extended atmosphere radiated in emission lines and in the Balmer continuum [6]. The velocities of the absorption components increased from −600 km/s in February to −1600 km/s in June, 1996 [7]. Strong forbidden lines of ions in high state of ionization, such as [Fe VI], [Fe VII], and [Ca V], appeared during the period from May 30 through July 1, 1997 (JD 2450598–2450630), which marked the transition to the nebular stage.

The star was first detected at radio waves at 6 cm on December 13, 1996 (JD 2450432), 362 days after its optical maximum [8]. The curve of the radio flux and radio maps obtained with MERLIN radio telescope were published by Heywood [9]. At first, the radio source could not be resolved and remained opaque for radio waves. Then the source was observed to undergo a transition to a radio-transparent stage. It was resolved for the first time on March 4, 1998 (JD 2450938). Later observations [9] showed the envelope to have a cloudy structure, and varying optical depth of the ejecta was found to show up significantly in its appearance at some times. HST/NICMOS failed to detect the envelope in the $1.87 - 2.37\ \mu$m wavelength interval [10]. Later radio observations of the envelope expansion corroborate the heliocentric distance of 2.4±0.4 kpc [11, 12] and the expansion velocity of 210 km/s. Iijima [7] estimates the expansion velocity of the ejecta and the heliocentric distance of the star at 305 km/s and 2.8 kpc, respectively.

Ness et al. [13] detected X-ray radiation from nova V723 Cas on January 31, 2006 with SWIFT XRT space observatory. The source proved to be a supersoft X-ray source (SSS) with a spectral maximum at 0.4 keV. Its blackbody temperature as inferred from the energy distribution was 340000 K. Given that this observation was made during the 11th year after the maximum of the outburst, it can be concluded that V723 Cas has the record late X-ray stage among Galactic novae (it is followed by GQ Mus, which "turned on" at X-rays nine years after its discovery). The fact that we observe this SSS means that thermonuclear burning of the hydrogen-rich matter occurs at the surface of a white dwarf [14] and we observe the radiation of such a source directly and unabsorbed by the envelope.

Orbital light variations with a period of $0\overset{d}{.}69325\pm 0\overset{d}{.}00018$ were noticed since September, 1997 (JD 2450706), when they had an amplitude of $\approx 0\overset{m}{.}06R$ [15, 16]. The amplitude of the orbital light curve increased gradually since then. The light curve had a sawtooth shape (1998 and 1999) and then became similar to that of an eclipsing variable with a wide and highly asymmetric primary minimum. Shugarov et al. [17] studied the evolution of the shape of the orbital light curve in the $UBVRI$ bands during the period from 1996 through 2003. Observations show that in 2003 the V-band amplitude of the orbital variability increased to $1\overset{m}{.}3$ and the light curve became stable. The increase of the amplitude of the orbital variability was due to the dispersion of the envelope and decrease of its contribution to photometric bands.

Goranskij et al. [18] observed an episode of the white-dwarf envelope pulsations on September 19, 1999 (JD 2451441), on the 1373th day after the maximum, with a period of 0.062 days and maximum full R-band amplitude of $0\overset{m}{.}05$. Earlier, Schenker [19] discussed the possibility of radial pulsations in the envelopes of classical novae. He showed, based on linear and nonlinear computations, that internal stable parts of the envelope develop running-wave-type instabilities, which evolve rapidly into shocks. They ultimately appear as nonadiabatic radial pulsations. Drake et al. [20] observed such X-ray pulsations in the nova V1494 Aql with a period of $2498^{s}.8$ (0.028912 days). This nova was also a supersoft X-ray source.

The generally recognized outburst mechanism in classical novae (which is corroborated by model computations (see, e.g., [21])) is assumed to be a thermonuclear explosion in the hydrogen-rich matter accumulated at the surface of the white dwarf as a result of accretion in the binary. The white dwarf in a cataclysmic system is surrounded by a gaseous accretion disk supported by mass outflow from the red-dwarf companion. The gas (H + He) reaches via the accretion disk the surface of the white dwarf and forms there a hydrogen envelope — the so-called "ocean". Mixing enriches this ocean with heavier elements of the white dwarf material [22]. A thermonuclear explosion of hydrogen occurs at the bottom of the hydrogen ocean when the mass of this element reaches the critical level, and the presence of C, N, and O elements in the white dwarf promotes the thermonuclear reaction. The elemental abundances in white dwarfs determine to a large extent the spectral peculiarities and development of nova outbursts.

After the explosion, the dwarf system is embedded deep inside the "fireball" made up of the ejected matter. Spectroscopic observations show that in the case of V723 Cas this "fireball" appeared as an F-type supergiant with a slowly expanding quasi-stable photosphere. Would the accretion disk be preserved in such an explosion? What happens with the cool companion in such a hot environment? Retter [23] assumed that "the nova outburst disrupts the accretion disc only in intermediate polars because their discs are less massive than in non-magnetic systems and their inner parts are depleted". Examples of such novae include GK Per and DQ Her. In nonmagnetic systems explosions only distort the disk, which then again becomes stable. Systems with strong magnetic fields — polars — have no accretion disks at all and V1500 Cyg is an example of such an object. However, during nova explosions the envelope expansion velocities may reach 5–7 thousand km/s, which exceed the velocity of gas motions of the accretion disk by one order of magnitude and therefore even nonmagnetic systems may fail to maintain their disks.

Such a slow nova as V723 Cas is most likely to preserve its disk because of the low velocity of the ejecta. Moreover, we may further assume that the cool component, which for a long time (three months) resides inside the "fireball", should heat up, the envelope of the cool companion should expand, and the mass-transfer rate in the system should increase significantly. This should result in the formation of a massive accretion disk around the burning white dwarf inside the common photosphere surrounding the system [24]. In this case, the instability of such a massive disk and recurrent episodes of the infall of its matter onto the surface of the white dwarf (where nuclear burning continues) may cause strong outbursts observed during the declining branches of the light curves. Variations of the accretion disk and components of the cataclysmic system where a thermonuclear explosion had occurred have not yet been studied. One more reason why V723 Cas is a very good object to study such processes is that the orbit of this system is possibly strongly tilted. Large-amplitude orbital variability is indicative of the large orbital inclination. It would be of interest to study this star not only during its pre-maximum stage, but also during later stages, while it remains inside the optically thick gaseous envelope, and also during the process of the separation of the system and its gaseous envelope.

In this paper, we analyze the results of multicolor $UBVRI$ photometry and the results of 11-year long monitoring of V723 Cas after its outburst. We also analyze the spectra taken with the Russian 6-m telescope during late outburst stages starting from January, 2001, which supplement substantially the data published in other papers.

2. PHOTOMETRY

Because new photometric standards have been developed based on CCD observations of faint stars in the neighborhood of V723 Cas, we repeated the pre-outburst photometry of the nova on DSS plates (the photometric accuracy is $0^{m}.10$):

JD hel. 2435016.820	$18^{m}.60$	B	POSS I
35016.836	17.36	R_C	POSS I
47766.879	18.56	B	POSS II
48180.801	17.14	R_C	POSS II.

We began observing V723 Cas on August 30, 1995, six days after its discovery, and continue observations until now. In this paper we report the data obtained prior to October 27, 2006. Table 1 gives the information about the observatories, telescopes, and instruments employed, as well about the observers involved. Observations made in Russia, Kazakhstan, and Ukraine include multicolor photoelectric and CCD data obtained in the passbands of the UBV, $WBVR_J$, BVR_JI_J, and $UBVR_CI_C$ photometric systems (R and I in the Johnson and Cousins systems), and single-filter (V, R, or I) monitoring. For example, V-band data include a total of 3843 observations made during 844 nights. Observations made in Israel include 2106 V-band measurements and U, B, R and I-band observations in 27 nights.

Table 2 lists the available photometric measurements for stars in the vicinity of V723 Cas. The

Table 1. Series of photometric observations

No.	Observatory	Telescope	Instrument	Seasons	Observers
1	SAI, Moscow (Russia)	70-cm	UBV photometer[1]	1995–1999	G,K1,Sh1
2	SAI, Moscow (Russia)	70-cm	BVR_J photometer[2]	1998–1999	G,Sh1
3	SAI, Moscow (Russia)	70-cm	$WBVR_J$ photometer[3]	1998	G,Sh1
4	SAI, Moscow (Russia)	70-cm	UBV photometer[4]	1995–1996	G,Sh1
5	SAI, Moscow (Russia)	70 и 30-cm	CCD SBIG ST-6, ST-7 (BVR_JI_J)	1998–2005	G,K1,Sh1
6	INASAN, Zvenigorod Station (Moscow Oblast, Russia)	60-cm	UBV photometer[1]	1997–1998	G,K1,Sh1
7	SAO RAS, Karachai-Cherkessia (Russia)	100-cm	CCD K-585, EEV 42-40 ($UBVR_CI_C$)	2000–2006	B,G
8	CrAO (Ukraine)	38-cm	CCD SBIG ST-7 (BVR_JI_J)	1998–2002	B,G,K2,Sh1
9	SAI, Crimea Station (Ukraine)	60-cm	UBV photometer[5]	1995–2002	M
10	SAI, Crimea Station (Ukraine)	60-cm 125-cm	CCD SBIG ST-6, ST-7, ST-8 (BVR_JI_J)	1998–2006	B,G,K2,Sh1
	SAI, Crimea Station (Ukraine)	50-cm	CCD Meade Pictor-416 (V)	2005–2006	G
11	Tien-Shan Observatory (Kazakhstan)	48-cm 100-cm	$WBVR_J$ photometer[3]	1995–1996	G,K1,K3,P
12	Wise Observatory (Israel)	100-cm	CCD Textronix 1K ($UBVR_CI_C$)	1995–1998	R,Sh2

Remarks to Table 1.
Photoelectric photometers: [1] — single-channel photometer developed by I. M. Volkov and S. Yu. Shugarov with EMI 9789 photomultiplier and UBV filters; [2] — same photometer with FEU-79 photomultiplier and BVR_J filters;
[3] — four-channel photometer with dichroic plates developed by V. G. Kornilov and equipped with $WBVR$ filters; [4] — two-channel photometer developed by A. K. Magnitskii with two FEU-79 photomultipliers and UBV filters; [5] — single-channel photometer developed by V. M. Lyutyi with UBV filters.

Observers: B – Barsukova E.A., G – Goranskij V.P., K1 – Karitskaya E.A., K2 – Katysheva N.A., K3 – Kusakin A.V., M – Metlova N.V., P – Pogrosheva T.M., R – Retter A., Sh1 – Shugarov S.Yu., Sh2 – Shemmer O.

magnitudes of standard and check stars for photoelectric photometry were determined with respect to the UBV standard around V592 Cas [25] and with respect to the nearby stars of the $WBVR$ standards from catalog [26]. Here W is the ultraviolet photometric band introduced by Straizys [27]. The bands of the U, B, V and R, I photometric systems of our photoelectric and CCD photometers were computed in accordance with the reaction curves of the standard Johnson and Cousins systems and have small coefficients of the color equations.

The spectrum of V723 Cas contains many emission lines and therefore measurements with different instruments may differ systematically in colors and magnitudes. Experience shows that, like in the case of other novae, such discrepancies are impossible to eliminate via color equations derived from observations of normal stars. These systematic discrepancies

Table 2. Photometry of stars in the neighborhood of V723 Cas

Star	R.A.(2000)	Decl.(2000)	$U(W)$	B	V	R_J	I_J	Remarks
BD+53°216	$1^h05^m36^s.3$	$54^o07'52''$	$9^m.31$	$9^m.69$	$9^m.59$	-	-	comp. star, phe
			(9.361)	9.715	9.599	9.452	-	
BD+53°222	1 06 10.5	54 09 19	10.35	10.05	9.95	-	-	check star, phe
			(10.057)	10.135	9.933	9.740	-	
BD+53°219	1 05 58.0	54 09 18	12.38	10.78	9.38	-	-	
BD+53°220	1 06 04.6	54 11 59	9.95	9.98	9.51	-	-	
GSC 3668.2051	1 04 55.0	53 58 09	(14.56)	14.07	12.70	11.58		
GSC 3668.0884	1 04 49.8	53 59 44	(14.07)	13.99	13.24	12.56		
	1 04 52.7	54 01 24	(16.4)	16.21	15.11	14.11		
	1 04 53.9	54 02 01	-	18.37	16.88	15.47		
C1	1 05 16.5	54 00 46	15.55	15.44	14.72	14.04	13.66	comp. star, CCD
C2	1 05 20.3	54 00 43	17.26	16.12	14.98	13.91	13.24	check star, CCD
GSC 3668.1121	1 05 07.0	53 59 12	11.56	11.78	11.51	11.40	11.24	var, NSV 15236

are usually due to strong emission lines, which are located near the boundaries of the filter transmission curves. These boundaries slightly change from one filter set to another, or show a temperature dependence, which differs from one filter set to another. Thus strong [O III] emission lines at 4996 and 5006Å, which are typical of novae and which are located near the boundaries of the B and V bands, cause biases of up to $0^{\text{m}}.5$ and accidental uncertainties in both passbands, which are beyond the control. In most of the cases, systematic deviations between different series of observations can be eliminated or minimized by introducing constant corrections inferred from observations made with different instruments simultaneously or at close time instants. In other cases, such corrections may vary as a function of color indices. In some cases, they may remain constant only over a limited period of time due to variations that occur in the spectrum of the star. We faced all these kinds of problems when observing V723 Cas. Sometimes, during strong spectral variations, we found opposite trends in the colors measured with different instruments, and we found no way how to eliminate these systematic discrepancies in colors. We tried to use simultaneous measurements to reduce UBV and W photometry to the longest observing series — that obtained by N.V. Metlova who used the photoelectric UBV photometer of Lyutyi. We used the same method to reduce R-band observations to the Tien-Shan R band whose reaction curve is close to that of Johnson's R_J band.

The photometric standards in the BVR_JI_J bands for CCD observations were set with respect to Mendoza's [28] star sequence in the open cluster χ and h Per. We verified this reduction in the B, V and R_J bands by analyzing the photoelectric photometry of faint stars of this sequence (Table 2) and found deviations to be small. However, for the I band we have neither sufficient number of stars referred to various standards nor sufficient number of simultaneous observations made with different instruments and therefore our reductions in this filter remain approximate.

To supplement our data, we use published observations [3, 11], which were also obtained with different instruments. We use the same method to reduce separately each of these series to the same observing set of N. V. Metlova. In addition, we also use the CCD observations of Ohshima and Kosaka [29], which were made prior to the discovery of the star, in order to represent the earliest stages of the outburst.

We found the brightest star in our CCD frames — GSC 3668.1121 (also known as NSV 15236) — to be variable over the $11^{\text{m}}.78-11^{\text{m}}.93$, $11^{\text{m}}.49-11^{\text{m}}.60$, $11^{\text{m}}.33-11^{\text{m}}.46$, and $11^{\text{m}}.12-11^{\text{m}}.21$ intervals in the B, V, R_J, and I_J bands, respectively. It is a B6.5V-type star with the mean color indices of $B-V=0^{\text{m}}.31$, $V-R=0^{\text{m}}.15$, and $R-I=0^{\text{m}}.23$. It has a sinusoidal light curve with a period of $18^{\text{d}}.9$. It may be an ellipsoidal variable (of the ELL type) with the orbital period equal to twice the photometric period, $37^{\text{d}}.8$. We used this star as a comparison star for our CCD observations made during the 1997 season and then excluded it from our list of comparison stars.

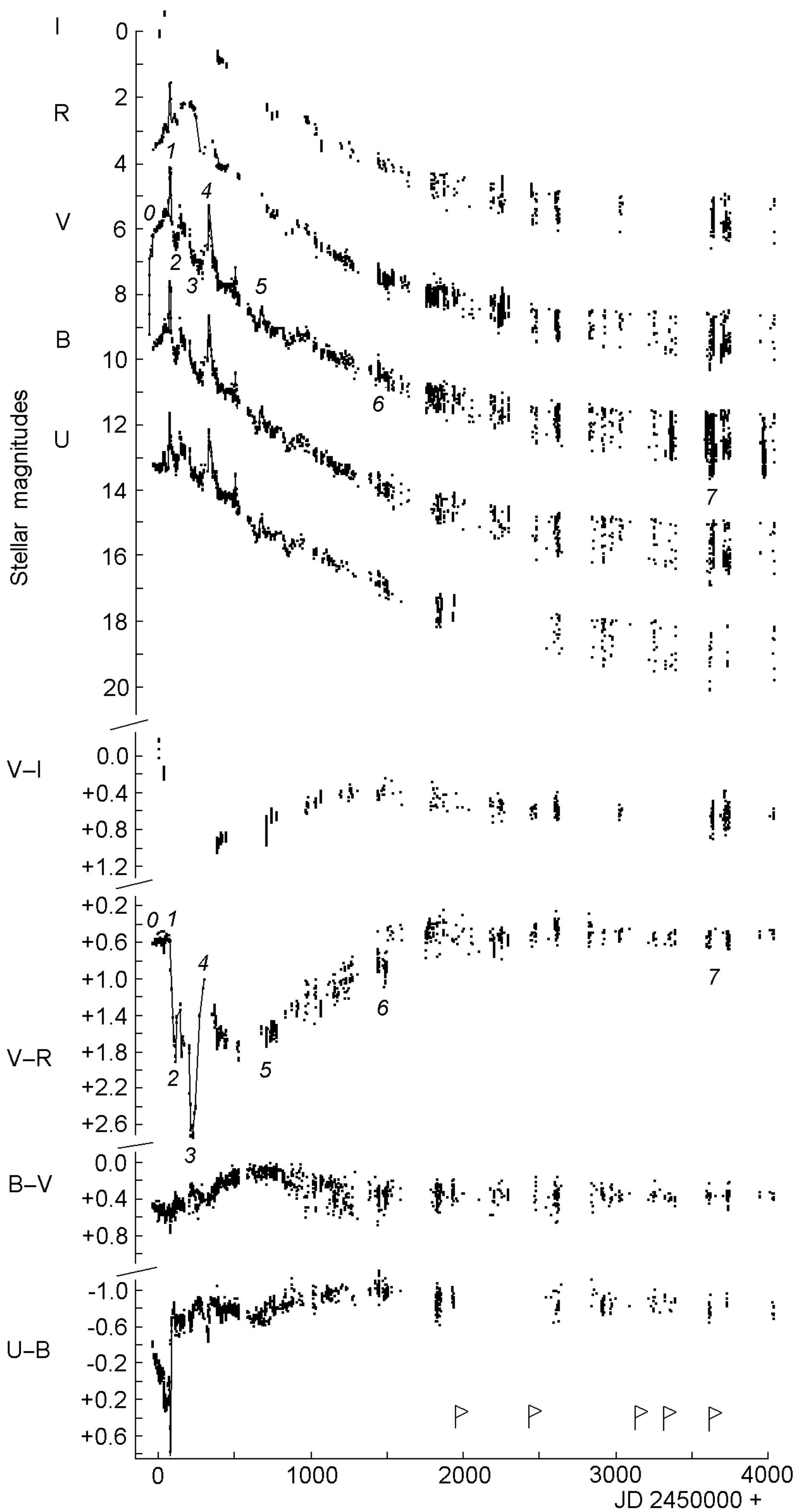

Fig. 1. Light and color-index curves of V723 Cas. Magnitudes are on an arbitrary scale (we give the magnitudes at maximum light in the Introduction section of this paper). Flags indicate the time instants when the spectra were taken with the Russian 6-m telescope. The numbers indicate the remarkable episodes of the outburst development described in the text.

3. LIGHT AND COLOR CURVES DURING THE OUTBURST

Figure 1 shows the light and color-index curves of V723 Cas. In this figure we use a single magnitude scale with each light curve shifted arbitrarily relative to this scale. This shift for each particular light curve can be determined from the magnitudes at maximum light, which we give in the Introduction. The light and color-index curves in the bands of the UBVR system, their details and some of monitoring series are available on the Internet [30].

Figure 2 demonstrates the tracks of the nova V723 Cas in the color-color diagrams $(U-B)-(B-V)$ (a) and $(V-R)-(B-V)$ (b). Each data point in Fig. 2 represents a mean averaged over all measurements made during a single night. Also shown are the sequences of normal stars. The sequences of luminosity class V, III, and I stars in Fig. 2a are drawn in accordance with [27]. Figure 2b shows only the main sequence (luminosity class V) stars in accordance with [26]: on this scale giant stars lie close to main-sequence stars. The same numbers mark the main outburst stages in Figs. 1 and 2.

In the light curves of V723 Cas (Fig. 1) the pre-maximum stage at JD 2449960 − 2450058 is marked as (*0–1*). It ended with a five-day long outburst with a maximum at about JD 2450069. The initial decline of the light curve is superimposed by five outburst episodes, which occurred during the time interval JD 2450058–2450700, and the sixth weak brightening can be seen near JD 2450900. These outburst episodes appear either as individual outbursts lasting from several days to several dozen days or as recurrent outbursts lasting for up to 100 days. They alternate with quiescent-state periods of lower brightness or with brightness decreases before the next outburst. The dispersion of measured magnitudes gradually increases up to 2^m during late stages of brightness decline. This effect is not due to increasing errors of observations of the fainting star, but a manifestation of the periodic orbital variability with gradually increasing amplitude.

During the pre-maximum stage the magnitude and color indices vary nonmonotonically. The V-band magnitude increases by $0\overset{m}{.}6$ and the $B-V$ and $V-R$ color indices vary between $0\overset{m}{.}45$ and $0\overset{m}{.}65$ and between $0\overset{m}{.}5$ and $0\overset{m}{.}7$, respectively. Variations of the $U-B$ color are most conspicuous: this color varies from $-0\overset{m}{.}40$ to $+0\overset{m}{.}25$, i.e., the ultraviolet (UV) excess decreases. At the middle of the pre-maximum phase the star moved to the normal-star sequence in the color-color diagrams. At this time, the star is known to have had a continuous spectrum with absorption lines and weak emission components. See [7] for a review of interstellar-reddening estimates. The above author ultimately adopts $E(B-V) = 0\overset{m}{.}57 \pm 0\overset{m}{.}05$. This implies an interstellar-reddening corrected color index of $(B-V)_0 \approx 0\overset{m}{.}0$ in the pre-maximum phase and at maximum light, putting the nova into the domain of the diagram occupied by normal late B – early A-type stars. This is inconsistent with the mid-F [6] or F0Ia [4] absorption-spectrum type. The *extinction-distorted* color indices of the nova actually correspond to the energy distribution of a late F-type star (Fig. 2a). This possibly means that either most of the authors overestimated the color excess by a factor of three to four or the classification of the spectra at the pre-maximum stage is wrong.

After the maximum light at 2450069 (*1–2*) the color indices of the nova in the $UBVR$ system changed sharply. In the $(U-B)-(B-V)$ diagram (Fig.2), the nova passed through the point where its reddening-corrected color indices became equal to those of a normal F0Ia type star. However, the star developed UV and red color excesses and moved far away from the sequences of normal stars. Chochol and Pribulla [3] explained this phenomenon by the ejection of the dense envelope after the first outburst. The same authors observed the ejection of a new envelope of lower mass during the second outburst (Max = JD 2450135), after which the $V-R$ color index reached its record high value of $+2\overset{m}{.}8$.

Other novae with a single maximum also exhibited a similar increase of the $V-R$ color index, which appeared as a single feature on the color-index curves. However, in the case of V723 Cas this is a recurrent increase, it has two or more maxima (*2–3–4* in Fig. 1). We explain this feature of the light and color curves of novae by the expanding envelope's transition into an optically thin state by parts and not simultaneously, resulting in an abrupt decrease of the radius of the photosphere during every event. As a result, hydrogen atoms recombine in a large volume of gas above the common photosphere, Balmer emissions enhance, and the enhancement of the H_α emission results in the increase of the $V-R$ color index. At this time, the gaseous envelope still remains sufficiently dense, and forbidden lines do not form (see [4, 12]). In V723 Cas this transition to optically thin state was triggered by a shock and by mass ejection during the first outburst, however, the process of recombination was later terminated by the mass ejection in the second outburst (the radius of the photosphere increased for a short time and the volume of gas in the optically thin state decreased). After the second outburst the nova had the reddest color ($V-R = 2\overset{m}{.}8$), which could be seen conspicuously in the ocular of the telescope. The UV excess is most likely caused by the enhancement of the Balmer continuum due to recombination of hydrogen.

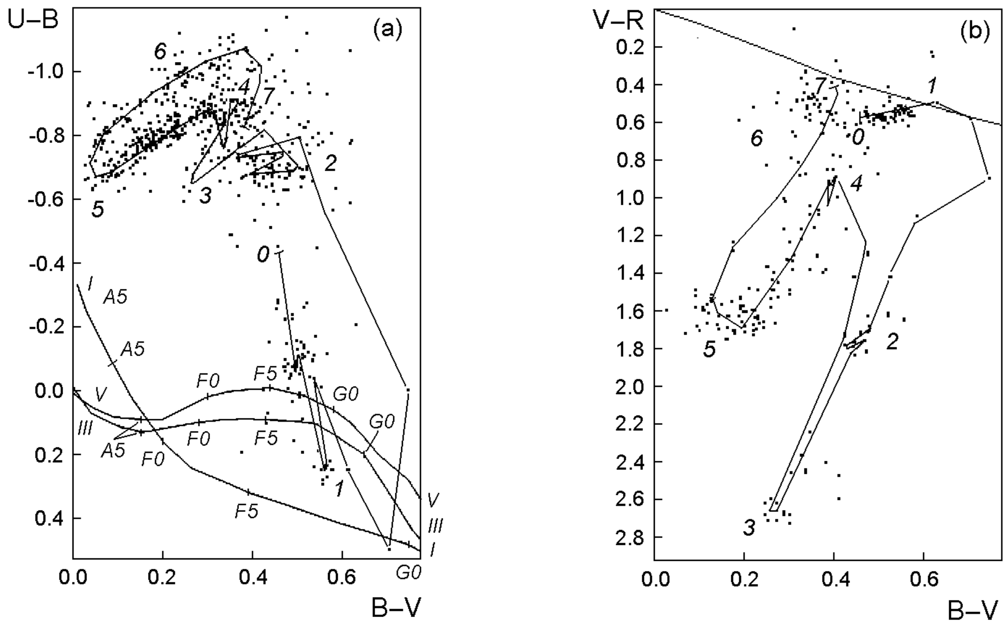

Fig. 2. Color-color diagrams $(U-B)-(B-V)$ (a) and $(B-V)-(V-R)$ (b) based on observations of V723 Cas. Tracks of the nova are drawn with numbers marking the same episodes of the outburst development as those indicated in Fig. 1. Also shown are the sequences of normal stars of luminosity classes I, III, and V (a) and the position of the sequence of normal stars of luminosity class V (b).

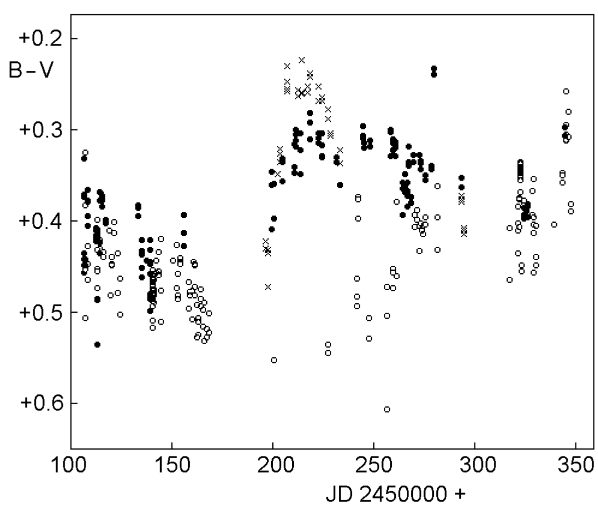

Fig. 3. Differences of $B-V$ color indices measured with different instruments in May–August, 1996, which are due to fast spectral variations. The filled and open circles and crosses show the observations made with the photometers of Lyutyi, Shugarov–Volkov, and Kornilov, respectively.

During this period (May – August, 1996) the reddening of the $V-R$ color index was accompanied by rapid spectral variations, which resulted in large discrepancies between the $B-V$ color indices measured by different instruments (Fig. 3). The instrumental B and V bands have very small color terms. However, the measured $B-V$ color indices vary with opposite trends and at different rates, making it impossible for the colors to be reduced to a standard system or at least to the system defined by one of the instruments. These discrepancies amount to $0\overset{\text{m}}{.}3$ in the color index.

The UV excess further increased after the third outburst and the star passed through a conspicuous loop (*4–5–6*) in both diagrams, first moving blueward (*5*) and then returning to the initial point. In the $(V-R)-(B-V)$ diagram the star even returned to the main sequence, i.e., into the domain of normal stars. While moving along this loop, the nova reached its extreme color-index values of $B-V=0\overset{\text{m}}{.}05$ and $U-B=-1\overset{\text{m}}{.}1$. In the upper part of the loop fast orbital color variations become appreciable and the scatter of data points increases. The size of this loop in the $(U-B)-(B-V)$ diagram for V723 Cas is not as big as in the case of other novae. The largest loops are those described by ONeMg novae, because of strong forbidden neon lines appearing in the UV part of their spectra. In the case of V723 Cas the size of the loop was bounded by the magnitude of the Balmer jump.

The outburst episodes observed during the initial decline of the light curve were found to exhibit the following characteristic behavior:

— outburst episodes appeared at all stages of the nova development. The first outburst ended the pre-

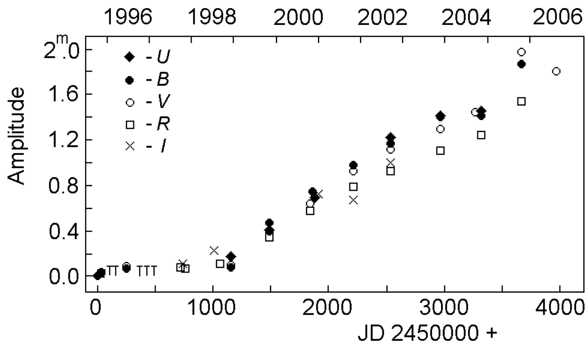

Fig. 4. Variation of the amplitude of periodic light variations in different filters. Also marked are the upper limit for the periodic component in the cases where such variations were not observed.

maximum stage and the last outburst occurred already in the nebular stage;

— the color indices became redder and the UV and red excess decreased with increasing brightness of the star;

— star brightness decreased below the average level before the second, third, and fifths outbursts. Chochol and Pribulla [3] describe this phenomenon as obscuration effect: "It is interesting that the stages of activity always occur after the obscuration of the hot component by transferred matter";

— successive outbursts are, on the average, 180 days apart [3], which follows from frequency analysis. However, this interval increases with time. Chochol and Pribulla [3] explain the 180-day periodicity and obscuration effect either: (1) by bursts of mass transfer from the red to white dwarf due to proper variability of the cool component or (2) by the presence of a third body — a cool giant — and bursts of mass transfer from this body during the passage of the periastron.

It is also safe to assume that the presence of outburst episodes is consistent with the formation and evolution of a massive accretion disk inside the ejected envelope of the nova. The disk feeds on the mass loss from the heated secondary. The disk in V723 Cas was preserved during the pre-maximum stage because of the low velocity of mass outflow during the explosion in this nova. Its outer edge shields Lagrangian point L1 from the "stellar wind" (which consists of particle products of thermonuclear burning) and from the pressure of radiation emerging from the surface of the white dwarf, and there are no barriers for mass outflow from the secondary component. Before each outburst episode the thickness of the accretion disk increases, it shields an increasingly larger fraction of stellar wind and radiation near its surface, and in the case of large orbital inclination we see obscuration effect. As its mass increases, the disk at a certain time instant becomes unstable and (possibly partly) falls down onto the surface of the white dwarf, thereby triggering a new outburst, development of shocks, and ejection of a new gaseous envelope.

4. ORBITAL LIGHT AND COLOR VARIATIONS

During and between the outburst episodes chaotic light variations were observed on time scales ranging from several hours to several days with amplitudes of up to $0\overset{m}{.}5$. We found no stable periodicities in these variations. The most significant periods mentioned in [3] were found in the quiescent intervals between outbursts: $0\overset{d}{.}6350$, and the closest to the orbital period, $0\overset{d}{.}6818$. Our independent observations later confirmed the second period.

An orbital period of $0\overset{d}{.}69325 \pm 0\overset{d}{.}00018$ was determined by Chochol et al. [15] and Goranskij et al. [16]. The latter authors also followed the early stages of the evolution of the orbital light curve. These data revealed the orbital periodic variability with an amplitude of $0\overset{m}{.}04$ as early as December, 1996. The time scale of light variations during this period was close to the orbital period, however, these variations did not coincide in phase with orbital variations. The phase coincidence of one of the light-curve fragments in December, 1996 may have been accidental, whereas other local minima have chaotically distributed orbital phases (Fig. 1 in [16]). Regular orbital variations appeared in late 1997. Intense monitoring from September 14 through November 15, 1997 (JD 2450706–2450768) allowed us to reveal sinusoidal light variations with an amplitude of $0\overset{m}{.}07$ and with a minimum that coincides in phase with the well-defined future primary maximum. The light curve shows both slow declining trends and rapid variations. Observations made in the fall of 1997 lead us to suggest that the entire system still remains under the common photosphere, whereas the outer parts of the envelope have already reached the nebular state.

In September–December, 1997 the light curve did not have the shape of a double wave, implying that the common photosphere is not an elongated surface coinciding with the equipotential surface as is the case for coalesced binaries, and does not rotate together with the components. Note that the light curve phased with the orbital period has the form of a single wave spanning the orbital period. Such a variability was most likely due to the nonuniform brightness distribution across the photosphere. The minimum brightness coincides in phase with the inferior conjunction of the cool component, and this minimum is due to the cold component shielding the flux from the hot central source.

Monitoring of V723 Cas performed at Wise Observatory in September 3–7, 1998 (JD 2451060–2451064) [16] showed that at that time the light curve

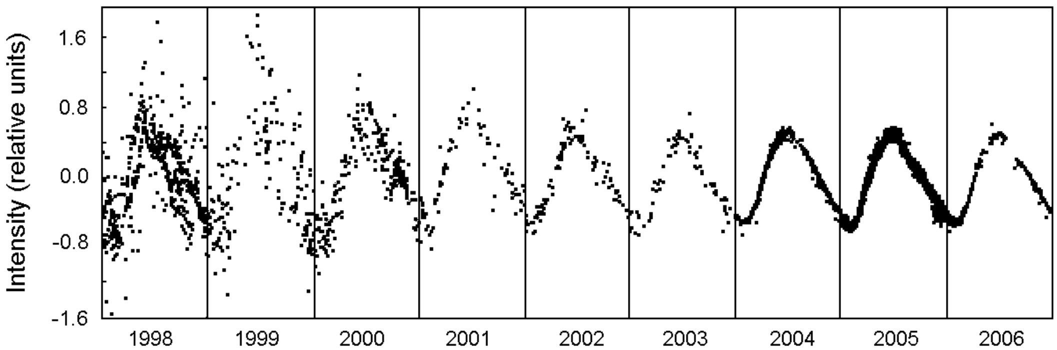

Fig. 5. Variation of the phased orbital V-band intensity curve with a period of $0^d_.693265$ in different years as a function of time with the trend of the gradual brightness decline in the intensity scale subtracted.

Table 3. Times of minimum light for V723 Cas

JD hel.24...	Rem.	JD hel.24...	Rem.	JD hel.24...	Rem.	JD hel.24...	Rem.
50009.569	*V*(n)	50767.45	WO	51467.64	SAI	53610.516	SAI
50009.638	*B*(n)	50849.226	SAI	51486.312	SAI(n)	53612.5950	SAI
50031.199	*V* WO	50968.454	SAI	51538.33	SAI	53628.5200	SAI
50031.234	*B* WO	51031.56	SAI	51842.666	SAI(n)	53633.3921	SAI
50260.392	*B*(n)	51061.35	WO	52200.390	SAI	53656.2497	SAI
50260.443	*V*(n)	51061.350	SAI(n)	52227.418	SAI	53701.3220	SAI
50381.46	WO	51063.46	WO	52473.544	SAI	53737.3555	SAI
50382.36	WO	51072.45	SAI	52611.498	SAI	53744.2944	SAI
50387.51	WO	51152.16	SAI	52623.288	SAI	53963.3941	SAI
50388.56	WO	51170.19	SAI	52819.4773	SAI	53965.4807	SAI
50428.401	SL/SP	51213.18	SAI	52914.4624	SAI	53972.3953	SAI
50706.369	WO	51438.53	SAI	53355.3824	SAI		
50720.964	WO	51441.27	SAI	53358.1570	SAI		
50757.706	WO	51445.41	SAI	53594.5650	SAI		

(n) — A normal minimum, the other minima are individual; WO — taken at Wise Observatory; SL/SP taken at Stara Lesna — Skalnate Pleso observatories; SAI — taken at Sternberg Astronomical Institute.

was already sawtooth-shaped. If we set the phase of minimum light equal to zero, the phase of maximum light is equal to 0.3–0.4, and at 0.6 the light curve shows signs of a certain decline in some of the cases, which may represent the secondary minimum. These may be features specific of the eclipsing light curve. Subsequent observations show that on the whole, the shape of the light curve remains stable (despite the variations of its level and decrease of chaotic variability), and the amplitude gradually decreases in all photometric bands (Fig. 4). Figure 5 shows V-band observations in the intensity scale for the last nine years beginning with 1998. The light curves are shown with the intensity trend subtracted. We used the following elements [24]:

$$Min = JD\ Hel.\ 2451842.666 + 0^d_.693265 \times E. \quad (1)$$

As is evident from Fig. 5, in the intensity scale both the amplitude of the orbital variability and the shape of the light curve have remained, on the whole, unchanged until now (2006). It is thus safe to say that the binary separated from the common envelope in 1998, but the contribution of the gaseous nebula — the explosion remnant — to the total flux decreases much faster than the contribution of the binary. No

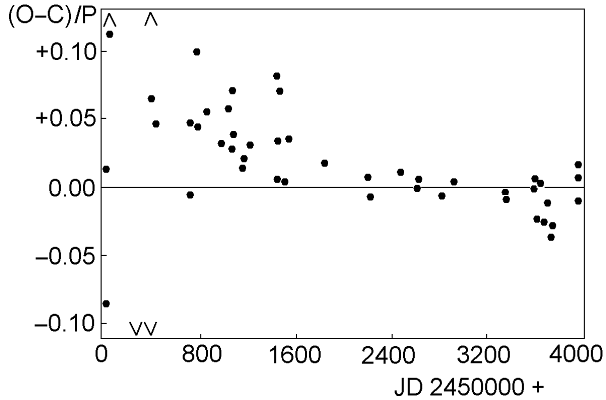

Fig. 6. The O–C diagram (in fractions of period) constructed with respect to linear elements (3). Some of the local minima of the curves do not fall within the given range, and they are marked by special symbols at the boundaries of the figure.

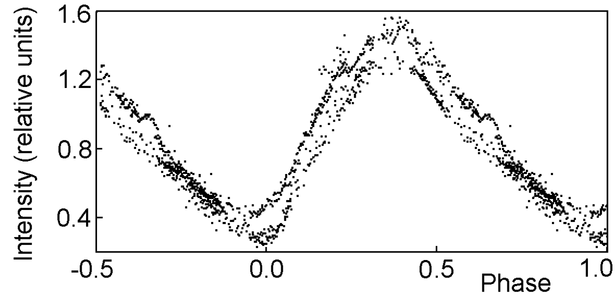

Fig. 7. Variation of the light-curve level in the second half of 2005. The star became fainter in the time interval JD 2453608–2453634. The decrease of the total flux was accompanied by a shift of the primary minimum (its phase increased) and the appearance of a step on the rising branch).

outbursts have been observed on the declining branch of the light curve after the system separated from the common photosphere.

The orbital period of V723 Cas is one of the longest among classical novae. It is the longest period among the orbital periods of novae in the list of Warner [31]. However, recurrent novae in systems with red giants have even longer orbital periods. For example, the orbital periods of T CrB and RS Oph are equal to 227.53 [32] and 455.72 days [33], respectively. Some researchers even classify these systems as symbiotic novae. The shape of the orbital light curve of V723 Cas resembles that of the recurrent nova CI Aql during its outburst of 2000 [34]. This nova also has a long orbital period, $0\overset{d}{.}618355$, which is close to that of V723 Cas. According to observations in the quiescent state, CI Aql is an eclipsing system and therefore the authors interpret such a shape of its light curve with a wide asymmetric minimum as an evidence for the eclipsing nature of the star. The wide wing at the decline branch of the primary eclipse implies the presence of a bright accretion disk.

The stable light curve in the intensity scale over the entire nine-year observing period allows the most accurate value of the orbital period to be determined using the Lafler–Kinman method [35], which consists in minimizing the light-curve dispersion. However, the use of this method is correct only on the assumption that the period did not change during the entire observing time. This method yields elements with the somewhat longer period:

$$Min = JD\ Hel.\ 2453972.4151(\pm 35) + 0\overset{d}{.}6932757(\pm 3) \times E. \quad (2)$$

Since 2001, we adopted the following elements:

$$Min = JD\ Hel.\ 2452611.498 + 0\overset{d}{.}6932773 \times E. \quad (3)$$

Elements (3) were inferred using the O–C method. We used individual times of minima and normal times of minima (i. e., the times derived from the average light curve) listed in Table 3. Figure 6 shows the plot of O–C as a function of time. As is evident from this figure, the orbital period increases. Whereas elements (1) are valid before 2001, elements (3) apply during the later period. Note that near JD 2453600–2453700 the times of some of the light minima fit neither elements (1) nor elements (3). These minima occurred during the 2005 season (we mark this season by the number (*7*) in the overall light curve in Fig. 1). Figure 7 shows the V-band light curve for this season (in the intensity scale). As is evident from this figure, the light-curve level "broke into two". In a narrow interval of Julian dates — 2453608–2453634 — the light-curve level dropped by 20%, and then returned back. Such an overall light decrease was accompanied by a substantial shift (by 0.05 in phase terms) of the primary minimum. The shape of the minimum changed too: a step appeared at the egress from the minimum near the phase of 0.10. It is evident from the analysis of the light curve (Fig. 7) that the light source that is responsible for such variations is located in the system so that it can be seen at the time of the primary minimum and at almost all orbital phases except for the phase interval 0.70–0.85, where the light curves merge. Substantial shifts of the phase of the primary minimum were also observed in August, 2006. The nature of these variations of the light-curve shape still remains unclear.

The shape of the primary minimum is also variable. A "flat bottom" was observed during some eclipses. In classical eclipsing stars the "flat bottom" appears during the eclipse in the cases where the components of the system have different sizes. Two cases are possible: total eclipse (when the larger component covers the smaller one) and partial eclipse (transit of the smaller component across the disk of the larger component). Judging by the small magnitude of color variations during the eclipses of V723 Cas, this flat bottom must form as a result of the transit of the secondary component across the extended accretion disk, whose size exceeds the diameter of the secondary component. In these eclipses bends can be seen in the light curves, and these bends can be explained by inner contacts — conjunctions of the stellar limb with the edges of the accretion disk during a partial eclipse. As is evident from the next three eclipses, the duration (d) of the flat bottom is not constant:

JD hel. 24...	d (days)
53355.382	0.0403
53656.250	0.0597
53744.294	0.0494

implying that the disk size changes. The flat bottom does not appear during some eclipses and the light decline is immediately followed by the rise of the light curve. In some cases the brightness varies between the inner contacts, or a "step" appears on the light curve in the middle of the eclipse. However, we noticed no steps on the declining or rising branches of the primary minimum, which would appear at the same phase. This means that we do not see at optical wavelengths the occultation or emersion of the photosphere or the surface of the white dwarf, where thermonuclear burning takes place. We therefore were unable to determine the duration of the eclipse of the white dwarf. Such an eclipse can only be revealed via far-UV or X-ray observations.

The local light minima in late 1996 (JD 2450379–2450440) are inconsistent with any elements and are chaotically scattered in orbital phase, although the time scale of light variations at that time was also close to the time scale of orbital variations. At that time the dwarf system has not yet separated from the common photosphere and light variations were not associated with the orbital rotation of the surrounding matter.

The study of periodic orbital light variations in the pre-maximum stage and at later stages with the common photosphere is of special interest, because it may provide information about the processes that go on inside the "fireball", i.e., the envelope ejected during the explosion. Earlier, before December, 1995 (JD<2450057), no stable short-term variations were observed [3, 16], however, at later stages in the quiescent state (JD 2450421–2450794) two possible periods — 0.6350 and 0.6818 days [3] — were revealed. Our periodogram analysis of all collected observations confirms only the second period of 0.6818 days during the same time interval. There are no other significant periods even if we eliminate slow trends of the light curve and outbursts. The chaotic component in the variations was very strong at that time.

Now that we have a well-determined orbital period, we can refer the events on the light curve to the corresponding orbital phases (ϕ), study the phase dependences for different types of chaotic variability. To this end, we performed several numerical simulations with our observation.

First, we eliminated the overall decreasing light-curve trend in the observations made during the common-photosphere stage (JD 2449960–2450700), and for the remaining data we constructed the phase dependences with elements (1). These dependences showed that outbursts, brightenings, and fadings are uncorrelated with the orbital phase and therefore characterize the entire photosphere. We then eliminated the brightest outbursts from this series and cleaned it of low-frequency noise. To this end, we used the Fourier method. We successively "prewhitened" the data of the periodic components of the frequency spectrum in the domain P $\gtrsim$ 10 days until the upper level of the spectral noise dropped below $0\overset{m}{.}03$. "Prewhitening" is a commonly used procedure, where the average smoothed light curve of the given period is subtracted from observations. We then used the method of moving average to smooth the residual orbital phase curve. The residual light curve exhibits a low-amplitude ($\sim 0\overset{m}{.}04$) orbital wave with minimum light at phase $\phi \approx 0.75$.

We then performed such a study separately for the pre-maximum stage and for the intervals of quiescent light between outbursts and obtained the following results.

In the pre-maximum stage (JD 2449960 − 2450058) the star's magnitude weakly depends on the orbital phase. Figure 8a shows the mean B- and V-band light curves. In both filters these curves have the shape of a single wave with the orbital period and the amplitude of $0\overset{m}{.}014$. These data include 592 observations in each filter. The phase of the minimum of the wave depends slightly on the filter and data set used. The minimum light falls within the phase interval $\phi = 0.8 - 1.2$. In the pre-maximum stage the nova was monitored extensively over two nights at Wise Observatory (Fig. 8b). The star was monitored over two close nights on JD 2450031 and JD 2450033 and the data obtained, even if uncleaned, but only averaged using moving mean, corroborate this result. The amplitude of these variations is equal to

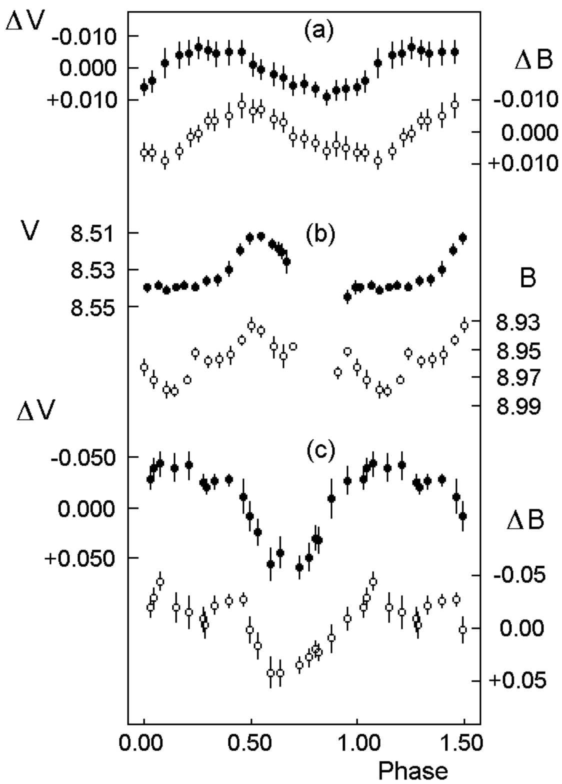

Fig. 8. (a) Mean orbital B- and V-band light curves based on all photoelectric observations in the pre-maximum stage. (b) B- and V-band mean orbital light curves based on the results of CCD monitoring in December 9 and 11, 1995. (c) Mean orbital B- and V-band light curves based on the data obtained from May 16 through July 25, 1996 (JD 2450220–2450290) in the quiescent state between the second and third outbursts. The mean curves are shown with eliminated long-period trends.

about $0^m_.02$ and the phase of the minimum is close to zero. Hence the low-amplitude variability in the pre-maximum stage corroborates the hypothesis of a "fireball" with nonuniform surface brightness, and lower brightness is observed at the phases when the cool secondary component is close to inferior conjunction with the white dwarf.

Light variations with the orbital phase were also found during the time interval JD 2450220–2450290, in the quiescent state after the second outburst (Fig. 8c). We use 106 observations in this case. Earlier, we interpreted this stage as the transition of the outer parts of the expanding envelope into an optically thin state, which is typically characterized by the strong red excess due to hydrogen recombination. One can again see a single wave on the light curve with the amplitude of $0^m_.10$ and $0^m_.08$ in the V- and B-bands, respectively. The nova was systematically fainter near the orbital phase of $\phi \approx 0.65$. It is assumed that because of the enhanced rate of mass transfer the accretion disk (inside the "fireball") had a thicker edge at the side facing the accretion flow. Because of the total thickness of the disk, the brightness decreased below the average level of brightness decline before the third outburst.

Light variations with orbital phase were not found during the following time intervals:

–JD 2450090–2450125, 152 V-band observations, quiescent state after the first outburst;

–JD 2450150–2450170, 41 V-band observations, light oscillations during the second outburst;

–JD 2450347–2450384, 489 V-band observations, during the light decline after the third outburst;

–JD 2450382–2450470, 710 V-band observations, in the quiescent state after the fourth outburst;

–JD 2450470–2450515, 94 V-band observations, light oscillations during the fifth outburst.

Figure 9 shows the V-band orbital light curves and color indices obtained in 2002 in the nebular stage. We use elements (1) in this figure. The filled circles and crosses show photoelectric UBV observations and $BVRI$ CCD photometry, respectively. Weak orbital variations can be seen in almost all colors except $U-B$ (we attribute it to the lower accuracy of observations in the U filter). The amplitudes of light variations are equal to about $0^m_.15$ in the $B-V$ and $V-R$ and to $0^m_.20$ in the $V-I$ color. During the minimum light the star becomes redder in the $B-V$, $V-R$, and $V-I$ colors, but at the same time bluer in the $R-I$ color. The fact that the $V-R$ and $R-I$ color curves are in antiphase is evidently due to the presence of the strong H_α emission line in the R band. Spectroscopy leads us to conclude that orbital variations of color indices depend on the relative contribution of bright emission lines of the envelope to the filter passbands (He II and H_β in the B filter and H_α in the R filter). Note that the contribution of emission lines remains virtually unchanged, whereas the spectral continuum exhibits variations of substantial amplitude as a function of orbital phase. The H_α line is the strongest line in the optical spectrum of the nova and therefore the amplitude of light variations in the R filter is the lowest compared to the amplitudes in other filters (see Fig. 4). The contribution of this emission line to the R passband amounted to 65% in January, 2001.

The orbital light curve of V723 Cas has an asymmetric sawtooth shape with a relatively more shallow declining branch and a steeper rising branch with the maximum light in the phase interval $0^p.35 - 0^p.40$. The amplitude of orbital variations amounts to $1^m_.9$ in the V band. The main sources of light in the system are the accretion disk and the part of the surface of the cool component that faces the disk. The hot spot at the surface of the cool component forms because

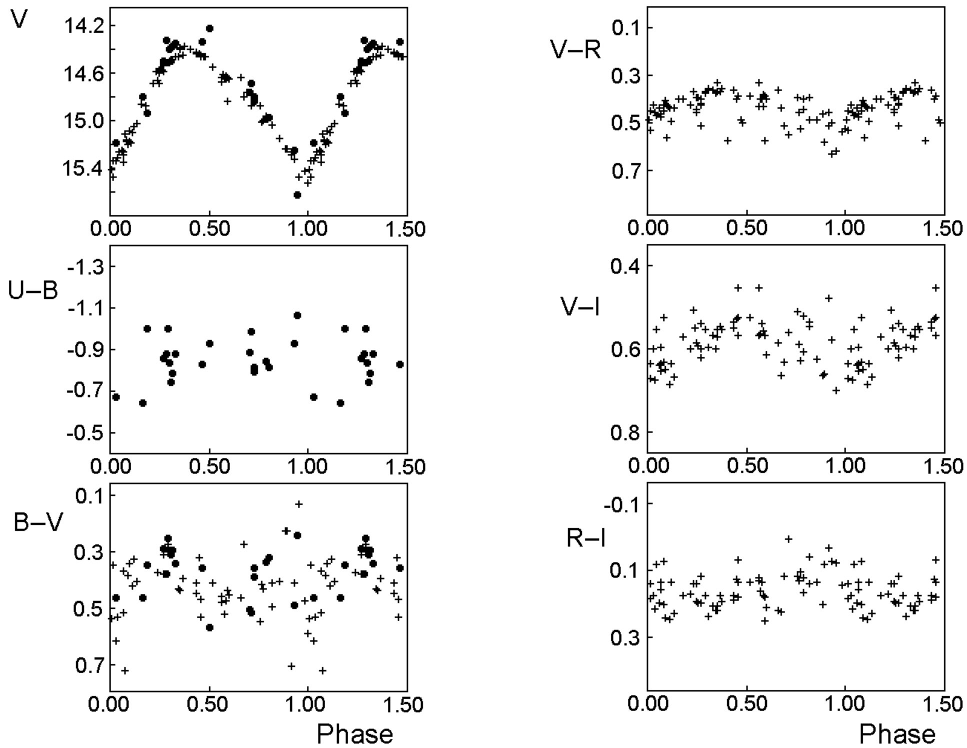

Fig. 9. Orbital variations of color indices according to observations made in 2002. The filled circles and crosses show photoelectric UBV observations and $BVRI$ CCD photometry, respectively.

Table 4. Spectroscopic observations of V723 Cas performed with the Russian 6-m telescope

JD hel.24...	Date	UT time	Phase	Wavelength interval (Å)	Resolution (Å)	Instrument
51933.450	2001.01.23	22:48:30	0.952	4320–6740	8.5	UAGS
52853.519	2003.08.02	0:28:00	0.105	6020–7250	3.5	UAGS
53209.495	2004.07.22	23:51:31	0.582	3980–5740	4.5	SCORPIO
53328.181	2004.11.18	16:14:35	0.780	3970–5740	4.5	SCORPIO
53621.496	2005.09.07	23:51:11	0.874	3960–5740	4.5	SCORPIO

of the reemission of short-wavelength fluxes arriving from the surface of the white dwarf in the ultraviolet and at soft X-ray wavelengths and because of the high-velocity stellar wind that forms as a result of thermonuclear burning of hydrogen at the surface of the white dwarf. This is the so-called “reflection effect”. Both sources of light may explain such a high amplitude of orbital variability only in the case of high orbital inclination. The mechanisms of this variability are the orbital rotation of the cool component with a hot spot and partial eclipse of the accretion disk by the cool component. The effect of these two mechanisms in the well-known X-ray system HZ Her (Her X–1) determines the symmetric light curve with the same amplitude as that of V723 Cas. The asymmetry of the light curve of V723 Cas can be due only to higher accretion rate compared to HZ Her, resulting in a thicker accretion disk in V723 Cas. Its outer edge is wider in the region of the collision of the gas flow at the disk edge with the flow falling from the cool component through Lagrangian point L1. Therefore in the case of high orbital inclination the hottest part of the accretion disk can be better seen immediately after the eclipse or near the first elongation, when the accretion flow is located on the opposite side from the observer.

5. SPECTROSCOPIC OBSERVATIONS

We took the spectra of V723 Cas in 2001–2005 with UAGS and SCORPIO spectrographs attached to the Russian 6-m telescope. The spectral resolution was 3.5–8.5Å. The star V723 Cas was a back-up object in applications for the observing time at the 6-m telescope and it was usually observed when weather conditions deteriorated: in gaps between clouds, through cirruses, or in the cases of poor (up to 5 arcsec) seeing. All spectra were taken with a long slit, allowing the sky background to be correctly subtracted. All spectra have a signal-to-noise ratio of at least 20–30 in the continuum near 5100Å. We reduced the spectra using the LONG context of MIDAS package. We usually took two spectra during every night and then coadded them. We then normalized all spectra by dividing them by the smoothed continuum. The plots show the relative intensities as fractions of the continuum level. To determine the line fluxes, we used our multicolor observations made during the same time period as spectroscopic observations with the correction applied to allow for the orbital phase. Table 4 lists the date, mid-exposure time (UT), orbital phase computed with elements (1), wavelength interval, and resolution. We made our spectroscopic observations during the nebular stage after the observations of Iijima [7] and Zhu and Hang [12].

The nova exhibits a typical nebular spectrum with strong forbidden lines of highly ionized elements. The hot stellar continuum is also very strong. The contribution of emission lines to the photometric B and V bands varied in 2001–2005 from 37 to 8% and from 29 to 7%, respectively. The slope of the continuum is consistent with the interstellar extinction of $E(B-V)=0^{\rm m}_{.}6$. The color indices of the stellar continuum with the emission-line contribution subtracted were equal to $B-V$=$0^{\rm m}_{.}38\pm0^{\rm m}_{.}10$ ($(B-V)_0$=$-0^{\rm m}_{.}2$) and $V-R$=$0^{\rm m}_{.}15\pm0^{\rm m}_{.}10$.

The spectrum taken in January 2001 (Figs. 10 and 11, the upper spectrum in each figure) resembles the latest spectra of 1997–1998 described by Iijima [7] and Zhu and Hang [12]. We verified the line identifications by the Coluzzi [36] and NIST [37] atomic databases and list the results of identifications and equivalent widths in Table 5. The inferred equivalent widths are accurate to about 5% in most of the cases. The relative intensities of emission lines changed substantially compared to their values in 1997–1998. The strongest lines in the optical spectrum are H_α, the [Fe VII]+[Ca V] blend at λ6086Å, He II λ4686Å, H_β, [Fe VII] λ5720Å, and H_γ. The presence of [Ca V] in the λ6086Å blend is confirmed by the presence of yet another [Ca V] line at λ5309Å.

In the spectrum taken in January, 2001 the He II λ4686Å line is stronger than H_β. The intensity ratio of these lines is reverse to that of December 1997 [12]. Later, the He II line at λ4686Å further increased relative to H_β. The fluxes in these lines are listed in Table 6 with the interstellar reddening of $E(B-V)$ = $0^{\rm m}_{.}57$ taken into account.

The flux ratio in the H_β and He II λ4686Å lines in the spectrum of a nebula is known to characterize the temperature of the source of ionizing radiation. The fluxes in the H I and He II emission lines depend on the radiation of the central star beyond the Lyman series and beyond the main series of He II. Ambartsumian [38] suggested a method for estimating the temperature of the central star of the nebula

Table 5. Identification of lines in the spectra of V723 Cas taken in 2001–2003

Line	λ(Å)	EW(Å)	Line	λ(Å)	EW(Å)
H_ϵ	3970	−0.6	[Ca V]	5309	−17.1
He II	4025	−1.8	[Fe VI]	5336	−3.4
C III	4069	−1.6	He II	5411	−26.0
H_δ	4101	−6.1	[Ca VII]	5619	−38.4
He II	4199	−1.9	[Fe VI]	5678	−5.8
H_γ	4340	−38.5	[Fe VII]	5720	−97
O II	4415	−2.5	[N II]	5755	−19.9
He I	4471	−2.5	C IV	5802	−5.7
He II	4541	−9.2	He I	5876	−10.3
[Fe IX]	4585	−3.0	[Fe VII]+[Ca V]	6086	−183
[Fe III]	4607	−1.6	He II	6120	−0.5
N III	4640	a blend	He II	6234	−2.4
C III	4650	a blend	He II+[S III]?	6311	−8.4
C IV+[Fe III]	4660	−1.9	[Fe X]	6374	var.
He II	4686	−146	He II	6406	−1.7
H_β	4861	−120	[Ar V]	6435	−6.3
[Fe VII]	4894	−13.0	O V	6466	−0.4
[Fe VII]	4942	−38	Fe XVII	6501	−1.6
[Fe VI]	4971	a blend	He II	6527	−1.8
[Fe VII]	4989	−11	N II	6583	−4.2
[O III]	5007	−20	H_α	6563	−660
[Fe VII]	5158	−25	He II + He I	6683	−7.5
[Fe VI]	5177	−12.9	He II	6890	−4
[Fe IV]	5234	−1.7	[Ar V]	7006	−4.6
[Fe VII]	5276	−38	He I	7065	−2.9
Not identified	5293	−5	[Ar III]	7135	−2.7

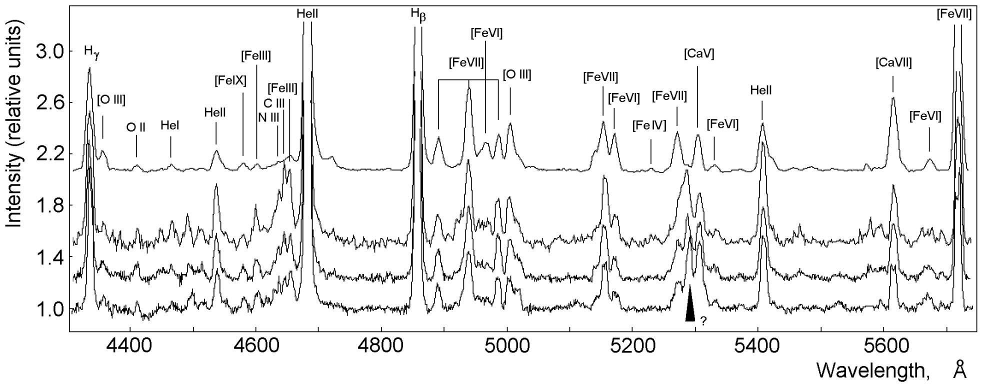

Fig. 10. Spectra of V723 Cas in the wavelength interval λ4300–5730Å taken on 23.01.2001; 22.07.2004; 18.11.2004, and 07.09.2005 (from top to down). The main emission lines are identified. The '?' symbol marks the unidentified line that appeared in the SSS phase.

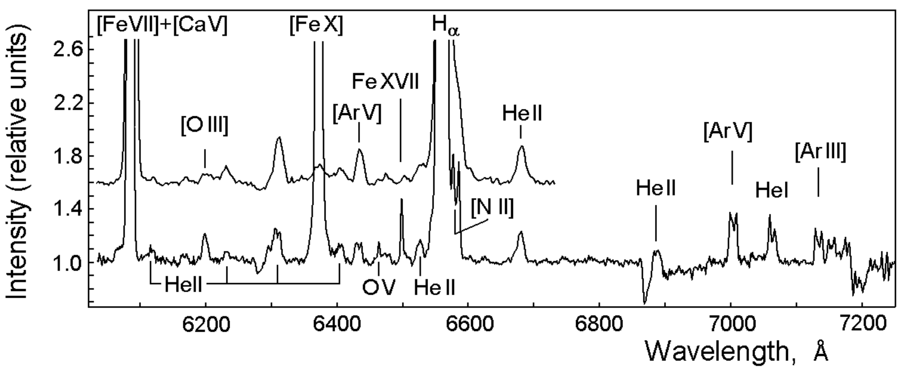

Fig. 11. Spectra of V723 Cas in the wavelength interval λ6020–7250Å. The dates of the spectra (from top to down) are: January 23, 2001 and August 2, 2003. The main emission lines are identified.

under the assumption of the Planck energy distribution in the spectrum of the star. This method was believed to overestimate (i.e., yield upper limits for) stellar temperatures (see. e.g., [39]). Beals [40] assumed that the number of emitted He II λ4686Å photons is equal to only half the total number of photons absorbed by He II ions in the far ultraviolet in the circumstellar nebula. We used Ambartsumian's formula and Beals' correction to estimate the temperature of V723 Cas and compared the result with the temperature determined by Swift space observatory [13] by fitting the soft X-ray energy distribution to the Planck formula. We found the best agreement to be achieved with the result obtained without applying Beals' correction. We list the resulting temperatures in the same Table 6, and in Fig. 12 we show the variation of the temperature of the SSS source in V723 Cas plotted against the optical (V) and radio light curves. Note that the shape of the He II-line profiles does not differ from that of hydrogen lines (see, e.g., Fig. 24 in [7]). In 2005–2006, the temperature of the central star in the V723 Cas system determined using this method was three-to-four times higher than the temperatures of white dwarfs and central stars of planetary nebulae. It is also evident (see Table 6) that the photosphere of the white dwarf does not cool down after the outburst as Goranskij et al. [18] assumed. On the contrary, its temperature increases with time. It is such a high temperature that causes the strong reflection effect observed in V723 Cas.

In the highest-resolution spectrum taken with the Russian 6-m telescope in August, 2003 (Fig. 13), the strongest lines have a bimodal structure. Iijima's spectra ([7], Figs. 23 and 34) in the nebular stage taken in 1998 with a higher resolution exhibit a more complex profile structure with numerous small peaks, which does not show up in our profiles. This points to the cloudy structure of the ejecta. However, higher-resolution spectra also show the general tendency for the enhancement of emission from the center toward the edge of the profile, which in low-resolution spectra appears as a bimodal structure. This means that the ejected envelope of the nova is, to a coarse approximation, a hollow sphere — an envelope consisting of large fragments — clouds. We therefore call this bimodal structure the "shell structure". The center of the H_α line has a velocity of −65 km/s. The expansion velocity of the envelope measured as half the difference of the velocities of the intensity maxima of these modes is equal to 170 km/s. The halfwidth of H_α line is FWHM = 580 km/s and the full width at the continuum level is FWZI = 1200 km/s. The envelope expansion velocity measured from other five emission lines in our spectrum lies in the 153–177 km/s interval and this scatter is likely to be partly due to measurement errors.

Because of such a high temperature of the ionizing source the spectrum of V723 Cas represents almost all weak He II lines. The enhanced brightness of the He II λ6311Å line may be due to blending caused by the [S III] [12] or S II [4] doublet. Forbidden sulfur lines can also be seen in the near infrared [41, 42]. The λ6683Å line may be a blend of He II and He I λ6678Å lines. He I lines in the spectrum of V723 Cas are relatively weak (see Table. 5). The Bowen blend C III/N III at λ4634–4651Å is also weak. At the same time, the [N II] λ5755Å line is relatively strong and this is also typical of novae in the nebular stage.

Lines of iron at various ionization stages are also very extensively represented in our spectra. Forbidden lines of ions in low ionization stages — [Fe III] – [Fe V] — were observed in the infrared [42] and later at optical wavelengths [7]. We identified two lines — [Fe III] λ4607Å and 4658Å— in our spectra. The [Fe IV] λ5234Å line can be seen only in the first spectrum of January 23, 2001, whereas in later spectra it does not exceed the noise level. We attribute the emission line at λ4072Å, which Iijima [7] identified with [Fe V], to the C III (4067.87, 4068.97, 4070.30Å) triplet, because our spectrum also shows another equally strong C III triplet as a part of the Bowen blend (4647.40, 4651.35, 4652.16Å). The coronal lines of [Fe VI] and [Fe VII] are among the brightest lines in the optical spectrum. Their behavior was described by IIjima [7] and Zhu and Hang [12]. Iijima [7] detected a weak [Fe X] emission, which can also be seen in the spectrum of the solar corona. Coronal lines, like hydrogen lines, have standard bimodal profiles (Fig. 13), implying that they form in the envelope. According to Iijima [7], the [Fe X] line did not appear until September, 1999; it was noticed for first time in late November, 1999 (JD∼2451510), and intensified after October 15, 2001 (JD∼2452197). We observed an order-of-magnitude increase of the [Fe X] flux from 3×10^{-14} to 3×10^{-13} erg/cm^{2}s (with the interstellar extinction $E(B-V) = 0^{m}.57$ taken into account) between January, 2001 and August, 2003 (JD 2451933–2452853). This enhancement of the line was observed against gradual light decline of the nova and decrease of the intensity of other nebular lines.

[O III] emission is represented by two weak lines λ4363Å and 5007Å. The spectrum also shows [Ar V] lines at λ6435Å and λ7006Å, and [Ar III] line at λ7135Å.

Later spectra taken in 2003–2005 show no appreciable changes in strong lines, however, several weak and narrow emissions appeared whose profiles do not exhibit the “shell” structure. These are the λ5293.2, 6466.4 and 6500.5Å lines. The authors of earlier works did not mention these lines. We identified the λ6466.4Å line with O V, and the λ6500.5Å line, with FeXVII. We show the profiles of these two lines in the right-hand part of Fig. 13. The appearance of these lines must evidently be due to the enhancement of the X-ray flux of the SSS. The λ5293.2Å line has not yet been observed in astrophysical objects and is absent in the list of Meinel et. al. [43]. Its position is close to that of the [Fe XIV] 5303Å line, which is observed in the solar corona and in the spectra of other SSS class objects. However, the 10Å difference does not allow us to identify this line with [Fe XIV]. Possible sources of radiation in these emission lines are the accretion disk or the side of the secondary component heated by X-ray radiation.

Our spectra also exhibit interstellar Na I D_2 and D_1 lines. Their total equivalent width is equal to 1.8Å, which agrees well with the 1.96Å value estimated by Zhu and Hang [12]. The spectrum also shows a diffuse interstellar band near λ6280Å (EW = 2.2Å).

6. RESULTS AND DISCUSSION

V723 Cas is a very slow nova with high orbital inclination. This circumstance allowed us to study the interaction between the envelope ejected during the explosion and the components of the binary. During the first months after the explosion the expansion velocity of the ejecta was equal to 160 km/s, which is insufficient to destroy the initial accretion disk near the white dwarf in the binary system. The accretion disk must therefore remain intact inside the “fireball” consisting of the products of explosion. In our opinion, the secondary component of the binary — a cool star, which during the period from 1995 to 1997 became immersed in a common photosphere, — heats up and expands as a result of the explosion, overfills its Roche lobe, and as a result, the rate of accretion through Lagrangian point L1 increases substantially. This process has not yet been simulated numerically. Cool dwarfs have convective envelopes, and therefore there may exist mechanisms for such heating.

Table 6. H_β and He II λ4686Å line fluxes and estimates of the temperature of the ionizing source

JD hel. 2400000+	F(Hβ) erg/cm^{2}s	F(HeII 4686) erg/cm^{2}s	r F(Hβ)/F(HeII)	T$_*$ (K)	Source
50800			1.86	195000	Zhu and Hang (1999)
51933.450	$3.53 \cdot 10^{-12}$	$4.35 \cdot 10^{-12}$	0.81	280000	this paper
53209.495	$4.84 \cdot 10^{-13}$	$8.90 \cdot 10^{-13}$	0.54	340000	–"–
53328.181	$4.02 \cdot 10^{-13}$	$6.03 \cdot 10^{-13}$	0.67	306000	–"–
53621.496	$3.16 \cdot 10^{-13}$	$4.80 \cdot 10^{-13}$	0.66	310000	–"–

Our observations of the nova in the pre-maximum stage showed the surface of the expanding photosphere surrounding the system to have a nonuniform brightness distribution because the accretion disk and the secondary component shield the radiation and stellar wind emerging from the central source. The accretion disk was rapidly refilled owing to the high rate of mass transfer. From time to time, instability caused part of the accretion-disk matter to fall down onto the surface of the white dwarf, where thermonuclear burning of hydrogen continued, and trigger recurrent outbursts of the star during its light-curve decline and the ejection of new expanding gaseous shells. This is a scenario of the first stages of the outburst that can be derived using the available observational facts. These facts are the periodic low-amplitude orbital variability in the pre-maximum stage with the minimum light near the phase of the inferior conjunction of the cool component and the light decline before outbursts, which can be explained by the increase of the disk thickness as the mass of the disk increases as a result of high rate of mass transfer from the secondary component.

Recurrent outburst episodes during the light decline are a common phenomenon in classical novae. In V723 Cas this phenomenon has not yet been sufficiently studied using spectroscopic methods except for the first outburst in December, 1995. DK Lac (N Lac 1950) is another nova with recurrent outbursts during the light decline, which were also observed in the nebular stage. The star was studied by Larsson-Leander [44] and Gorbatskii and Minin [45]. During each outburst the nebular spectrum of DK Lac evolved with the decrease of the degree of ionization at every increase of the star's brightness. The relative intensities of the He II and [O III] emissions decreased, those of He I and [N II] increased, and N III absorption lines appeared. Reverse changes occurred during the phase of outburst decline: the degree of ionization increased. Gorbatskii and Minin [45] explain it by the ejection of a new, denser envelope during each outburst. This envelope absorbs the short-wavelength ionizing radiation from the central star, thereby decreasing the degree of ionization. What is the nature of such an envelope?

The December 1995 outburst of V723 Cas was accompanied by the reddening of the color indices (Fig. 2) and the appearance of a late-type absorption spectrum (F0Ia). Other strong outbursts were accompanied by appreciable reddening in the $B-V$ color index despite the emission-line type of the star's spectrum. Hence dense and cool gas appears in the photosphere during outbursts. Such ejections cannot be caused by thermonuclear burning at the surface of the white dwarf. It only remains to assume that this cool gas precipitates onto the white dwarf from the massive accretion disk and is then accelerated by the stellar wind and radiation pressure to form a new expanding envelope. The nature of the instability of the massive disk remains unclear.

Another way to reveal the accretion disk inside the common photosphere consists in searching for superhumps on the light curve. The light curve of the nova V1974 Cyg exhibited such superhumps over a long time along with orbital light variations [46]. Superhumps on the light curve appear because of the precession of the eccentric accretion disk caused by strong accretion flow. Given that the orbital period of V723 Cas is very long, this implies a high mass ratio ($q = M_{donor}/M_{compact.} \sim 1$). The theoretical limit for superhumps is $q \lesssim 0.33$ and hence the theory predicts no superhumps for the binary considered. However, the results obtained by Retter et al. [47] for TV Col appear to suggest that this mass-ratio limit may be actually higher, up to 0.92. We analyzed observations of V723 Cas to seek for eventual secondary periods, but found no evidence for superhumps. The period of $0^{\mathrm{d}}.6818$, which is close to the orbital period, and which was found by Chochol and Pribulla [3] in the time interval JD 2450421–2450794, i.e. during the common-photosphere phase, can hardly be interpreted as the period of superhumps, because it is shorter than the orbital period.

Since July, 1997 the nova was already in the nebular stage, but later, in September—November, 1997 the system still remained under a common photosphere. The sawtooth-shaped orbital light curve was first observed in September 3–7, 1998 (JD 2451060–2451064). This asymmetric shape of the light curve then remains unchanged and only its amplitude varies. The asymmetry can be explained by the high accretion rate, eclipse of the accretion disk, and a hot spot on the side of the satellite facing the white dwarf. When the sawtooth-shaped light curve appears the temperature of the photosphere of the white dwarf exceeds 200000 K. At that time, the white dwarf still retained its envelope, which prevented the radiation of thermonuclear burning from reaching the surface, and pulsations could be excited in this envelope.

The flux of the [Fe X] line increased by one order of magnitude between January, 2001 and August, 2003 (JD 2451933 − 2452853) against the decrease of brightness and decrease of the fluxes of strong nebular emission lines. We associate this very event with the emergence of the supersoft X-ray source SSS. The origin of the coronal [Fe X] line in the spectrum of V723 Cas appears to differ from that of the corresponding line in the solar corona. The solar corona contains plasma with a temperature of several million degrees, which is formed by MHD-waves. The sources of ionization in the [Fe X] line in the spectrum of V723 Cas are X-ray radiation and particle fluxes that form as a result of thermonuclear burning at the surface of the white dwarf.

Iijima [7] analyzed the spectra of novae and wondered why very fast and extremely slow novae exhibit the [Fe X] line, whereas normal slow novae do not show this line in their spectra? The answer is evident: the [Fe X] line appears in the spectra of novae at the stages when we directly observe thermonuclear burning at the surface of the white dwarf, i.e., at the SSS stage. The nova outburst begins with a thermonuclear explosion at the bottom of the hydrogen envelope of the white dwarf, which formed as a result of accretion, and the X-ray radiation of thermonuclear burning is absorbed and processed by this ejected envelope. If burning ends before the envelope disperses and becomes transparent for X-ray radiation, we would see no SSS-class source and no [Fe X] line in the nebular stage. The nova V723 Cas appears to have a mechanism of refilling the resources of thermonuclear fuel via the accretion disk by increasing the accretion rate. We may therefore observe the long process of thermonuclear burning and the [Fe X] line over a long time. The source of soft X-ray radiation in V723 Cas is observed at the record late stage — on the 11th year after the outburst.

Earlier, X-ray radiation was discovered from some novae at late outburst stages. The first SSS-class source was discovered in GQ Mus by EXOSAT space observatory [48]. During the SSS stage, the visual brightness decline of this star ceased for one year (a plateau) after the initial 4^m- brightness decline. Note that when the SSS appeared, IUE recorded a recurrent outburst in the far ultraviolet, which did not show up in any way at optical wavelengths. At that time, high-ionization [Fe X] λ6374 Å and [Fe XIV] λ5303 Å coronal lines appeared in the optical spectrum what seemed to be an unusual phenomenon for fast novae.

The same plateaux were observed in the light curves of two reccurrent novae CI Aql and RS Oph during their outbursts in 2000 and 2006, respectively [34, 49]. The researchers associate the appearance of these plateaux with the SSS stage. In RS Oph the SSS-class source was observed by SWIFT space observatory and "turned off" on the 80th day after the outburst. The plateau was observed from the 40th through 75th day at the level of $y \sim 10\overset{m}{.}2$ ($\lambda \sim$5470Å, $\Delta\lambda$=230Å). During the plateau, the light curves in the wide bands of the UBV system show a slow decline which is likely to be due to the evolution of the emission component of the spectrum of the envelope. The contribution of emission to the y band of the Strömgren system is minimum and therefore the authors of [34, 49] suggest to use this very filter to monitor novae. Model computations showed that novae with the SSS stage owe the appearance of the plateau in their light curves to the accretion disk surrounding the white dwarf. The surface of the disk absorbs UV and soft X-ray photons emitted by the burning white dwarf and reemits part of the energy in the form of emission with lower temperature than that of the surface of the white dwarf. Without the accretion disk, models fail to develop plateau in their light curves.

As is evident from Fig. 12, the decline of the light curve of V723 Cas slowed down substantially and the mean brightness decreased only by $0\overset{m}{.}3$–$0\overset{m}{.}4$ in the B, V and R bands over the last four years (JD 2452600–2454100), remaining by $3\overset{m}{.}0$ and $2\overset{m}{.}7$ higher in the B and R bands, respectively, than before the outburst. The slow light decline can be explained by the decrease of the contribution of the expanding emission-line envelope. It is evident that V723 Cas has been in the plateau and SSS phases during the last four years (2003–2006).

7. CONCLUSIONS

In this paper we report the results of photometric and spectroscopic observations of V723 Cas, discuss the light and color curves of the nova in the $UBVRI$ photometric system based on our observations and on

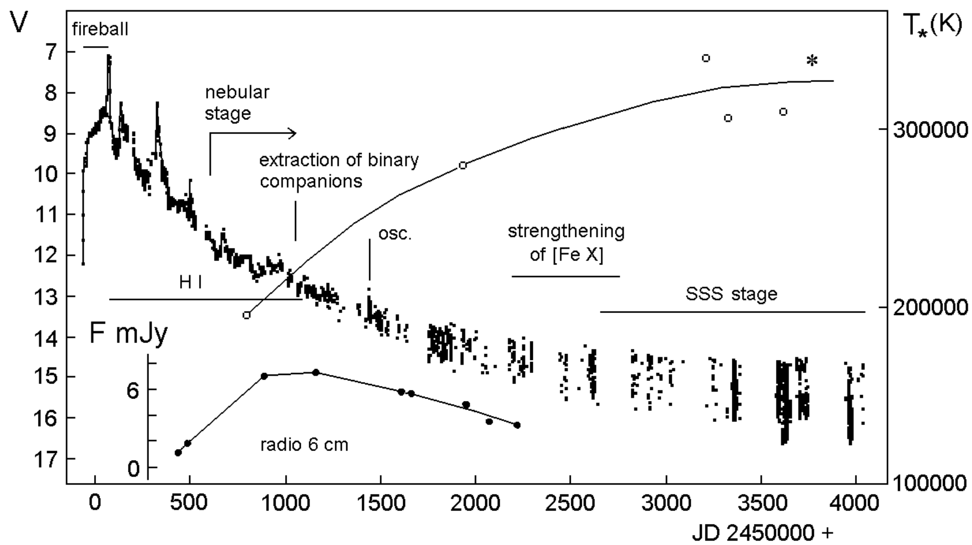

Fig. 12. Comparison of the V-band light curve of V723 Cas with the 6-cm radio flux and the curve of the temperature of the photosphere of the white dwarf. We identified the phases of "optically thick fireball", transition into optically thin state and hydrogen recombination (H I), nebular stage, and the SSS stage. We also indicate on the light curve the times when the components separate from the common photosphere and when they separate from each other, the time when oscillations were observed (*osc.*), and the time of the enhancement of the [Fe X] emission. The asterisk indicates the X-ray temperature of the white dwarf as measured by Swift space observatory.

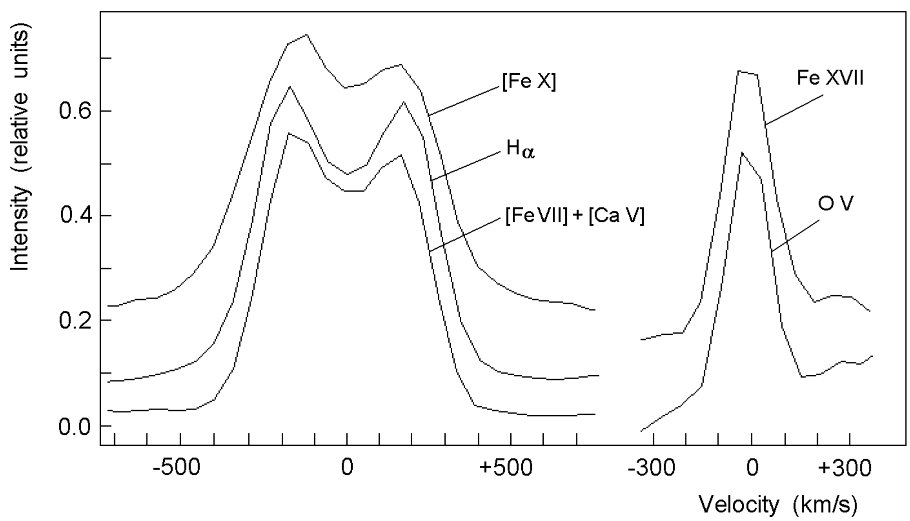

Fig. 13. Profiles of emission lines in the spectrum of V723 Cas taken on August 2, 2003. Left — profiles of the lines that form in the envelope. Right — profiles of the lines of very high degree of ionization, which appeared in the SSS phase.

published data by other authors. These data feature all stages of a typical classical slow nova, from the pre-maximum to the nebular stage.

Our observations reveal the following specific features of this slow nova.

(1) A three-months long pre-maximum stage during which the dwarf system resided inside a common expanding photosphere. We found that in the pre-maximum stage the star exhibits low-amplitude modulation with the orbital period of $0^{d}.693265$.

(2) The transition of the envelope into an optically thin state, which was accompanied by the recombination of hydrogen in a large volume of gas during which strong red and ultraviolet excesses were observed.

(3) Recurrent outburst episodes. We explain this phenomenon by the formation of a massive unstable

accretion disk inside the expanding envelope. Part of the disk matter periodically precipitated onto the white dwarf with hydrogen burning at its surface. Such a disk could have formed inside the expanding envelope of the nova as a result of the heating of the secondary component and increase of the rate of accretion from this component.

(4) Separation of the close binary from the common photosphere at the end of 1998, when the nova was already in the nebular stage. After the separation, outburst episodes ceased and the mode of the mass transfer through the accretion disk stabilized to a steady state.

(5) Periodic orbital variations with increasing amplitude. Their total amplitude was equal to about 2^m in 2006. The orbital light curve is asymmetric. The amplitude and shape of this light curve in different filters have remained almost constant in the intensity scale since September, 1998. We explain the asymmetric shape of the large-amplitude light curve by the eclipses of the accretion disk caused by the secondary component and by a bright hot spot at the side of the secondary component facing the white dwarf. This spot is due to the reemission in the photosphere of the secondary component of the flux of short-wavelength photons coming from the surface of the burning white dwarf. The asymmetry of the light curve is due to the edge of the accretion disk shielding the radiation of the central part of the disk. In the region of the collision with the accretion flow the edge of the disk widens. The system must have a large orbital inclination.

We analyzed the spectra of the nova V723 Cas taken in 2001—2005 with the Russian 6-m telescope at the beginning and continuation of the phase of supersoft X-ray source SSS. Spectroscopy shows a 10-fold increase of the flux of the [Fe X] emission associated with the appearance of SSS and the increase of the temperature at the surface of the white dwarf by 10^5 K. The [Fe X] line has a shell structure. After the SSS source turned on, narrow O V and Fe XVII lines appeared in the spectrum. These lines exhibit no shell structure and must form in the accretion disk or at the heated side of the secondary component. The high temperature at the surface of the white dwarf — 3.2×10^5 K — may explain the strong reflection (hot spot) at the surface of the cool companion in this system.

In conclusion, we point out the importance of performing X-ray observations of the eclipse of the star in the SSS phase, because such observations would allow us to determine the physical parameters of the system.

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