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Massive close binaries with early-type components

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A brief review of the study of massive close binaries system with the hot components carried out in Kourovka astronomical observatory is presented including such systems as CC Cas, SZ Cam, UU Cas, V368 Cas, BH Cen, SV Cen, LY Aur, V701 Sco. An attempt to explain the results of observations by the presence of circumstellar matter has been made. Some estimates of the circumstellar matter parameters are obtained.

Keywords: Stars: massive binary systems, observations, stellar characteristics, circumstellar matter, common envelope

1 Introduction

Massive stars are by definition the objects which may evolve to supernova outburst stage (SN). Plausible lower boundary of the mass for a single star as potential candidate to SN is determined to be equal to $\approx 8\ M_\odot$. Upper mass boundary of these objects is regulated by the pulsation instability condition. Observations of hot bright stars (Snow, Morton (1976); Barlow (1982)) detected noticeable mass loss due to intensive stellar wind. UV observations proved to be the most effective method of the study of matter outflow phenomenon. Series of resonance lines such as Mg II, Fe II, C IV, N V reliably diagnoses gaseous flow, the characteristic temperature and their density favorable for the formation of these lines. The study of UV spectra of hot massive stars with the bolometric luminosity of order $2 \cdot 10^4\ L_\odot$ allowed us to estimate the rate of mass loss equal to $10^{-7}\ M_\odot$/year. As it was discovered by *Copernicus* mission (Snow, Morton (1976)) registered velocity of stellar wind rapidly decreases with spectral class step-down. So, for example, mass loss in stars of B3 spectral class is almost not observed and lower boundary of noticeable mass loss is $M_{\rm bol} \sim -6^m$ that corresponds to Zero-Age Main Sequence (ZAMS) stars with masses of $\approx 15\ M_\odot$.

Accounting for mass loss observable in the majority of cases of O- and B-supergiants leads to the decrease of their mass by 10–20% during lifetime on the Main Sequence (MS) (Masevich, Tutukov (1988)). The theory of mass loss is still incomplete, which makes quantitative estimations difficult. A fraction of envelope matter is ejected into interstellar space due to stellar wind long before the explosion of the star.

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The evolution of single star losing mass due to stellar wind is identical to the evolution of the star being the member of a binary system although the rate of mass loss for the latter is higher (Ziolkowski (1977); Vanbeveren et al. (1979)). Theoretically it may be explained by smaller average value of surface gravity of semi-detached stars as compared with single stars, which intensifies the effect of stellar wind. The factor of rapid rotation of components produced by the synchronization of axial rotation with the orbital revolution of components is also an important contribution to mass loss.

In the case of massive binaries the mass loss becomes important both on the stage preceding Roche lobe filling and during fill-out stage. Mass loss steadily accompanies the evolution of the binary system but its rate may vary substantially. These processes become apparent in the formation of complicated gaseous structures between components as well as around the whole system.

2 The catalogue of Massive Close Binary Systems

To study typical observable features indicative of the presence of gaseous matter in hot massive binaries located near MS, a catalogue of the physical, geometrical, and evolutionary characteristics of these objects was compiled.

The catalogue contains information about spectral and photometric peculiarities of these stars as well as about their behavior in radio and X-range (Polushina 2004).

The catalogue includes 73 binaries for which spectral observations and light curves were obtained more than once. These systems presenting the basis of the catalogue of Massive Close Binary Systems (MCBS) were subdivided into seven groups depending on the type of configuration, for example, detached, semi-detached, and contact as

Table 1 Spectral types of MCBS.

	Star	Class	Spectral type	Remarks
1	OX Cas	*DM*	BIV; B6; B8; BO V; (B2V + B2V)	
2	XZ Cep	*DM*	B5; O9.5V; (B5+[A2]); (O9.5V+A2 III:); (B1.5II/III + BIV-B5)	
3	CW Cep	*DM*	B1.5; (B3+B3V:ea); (B0.5+B0.5IV-Vea)	H_α emission
4	EO Aur	*DE*	B5; (O9-B0+B3); (B3+B8); (B3V+B3V)	
5	[1] Sco	*SDZ*	(B3+B3); BI.5V+B6.5V); (B2+[B5])	
6	V382 Cyg	*KZ*	(B5+B5); (O7+O7); (O7+O8V); (O6.5+O7.5); (O9+B0)	
7	TN Mus	*KZ*	(O8.5V+O8); (B3+B3)	
8	V367 Cyg	*D,SD,K*	(B1III+B3III); (B8III+A1III); (F2e+[F5])	
9	GW Car	*SDE,KE*	B5; B1III:; B8; B0.5III; B6II-III; (F5-A+A3)	H_α emission
10	SV Cen	*SD,K*	(B1+B2); (B1V+B6.5II-III); (B1III+B4); B8	profiles of P Cyg-type
11	VV Ori	*DM,KM*	B1.5; (B1V+B4V); (B1V+B7V); (B2+B9); (B1V+B1V)	
12	AO Cas	*SD*	B9V; A9; (B3+B9); (B0.5+B3); (A0+[F0])	

well as giant and supergiant. Hereafter, a list of designations is introduced to specify classes of MCBS.

Analysis of catalogue data revealed several problems:

1. Inconsistency of estimations of spectral type for MCBS components obtained by various authors. In some instances the difference exceeds two spectral types whereas modern classification of stars allows us to determine spectral type of stars in O8–B2 range with accuracy less than half of spectral subtype.
2. The change of spectral type of components is marked for some MCBS. For example, spectral type of AO Cas primary component changes from O9.1 to O8.0 with the phase (Harwig (1987)). The primary spectral type of V640 Mon changes from O6.5 to O8.0 (Galkina (1967)).
3. Secondary lines in spectrum once appear then disappear.
4. A temporary appearance of spectral line profiles of P Cyg type.
5. The presence of an emission in H_α which sometimes is of irregular character.
6. Evidence for circumstellar envelopes which, as it was shown in a series of papers from the catalogue, appreciably affect line spectrum of the system as well as make a significant contribution to continuum.
7. Occurrence of spectroscopic eccentricities is not confirmed by photometry or strong discrepancy of its values obtained by various authors, e.g., V 861 Sco.
8. The differences in mass evaluation of MCBS components performed by various authors often exceed the accuracy of its definition declared in catalogues by 20% at the most. The most striking examples of this can be found in Table 2.
9. Analysis of catalogue data allows us to conclude that the form of light curve of one fourth of stars is the subject to variation, for example, we have no ambiguity for 14 systems regarding this issue (EA or EB). As for detached MCBS (their number in the catalogue is 17) seven of them show peculiarities in spectrum, six MCBS demonstrate period change, fifteen have apsidal motion or indications of existence of third body, and common envelope is observed for six MCBS.
10. Changes or distortion of light curves are marked for a quarter of stars from the catalogue.

The same may be seen for semi-detached MCBS (their number in the catalogue is nine): five of them have peculiarities in spectrum, the period change is marked also for five systems, and common envelope is observed only for three MCBS.

The abbreviations used in the tables are as follows:

1. *DE* – detached systems evolved from the main sequence;
2. *DM* – detached main sequence systems;
3. *DZ* – detached systems, both components are zero age main sequence stars;
4. *EA* – Algol-type light curve;
5. *EB* – β Lyrae-type light curve;
6. *Ell* – binary systems, whose variability is caused by ellipsoidal shape;
7. *EW* – W UMa-type light curve;
8. *GS* – systems with one or both giant and subgiant components;
9. *KE* – contact systems, evolved from the main sequence;
10. *KM* – contact systems, both components are main sequence stars;
11. *KZ* – contact systems, both components are zero age main sequence stars;

Table 2 Masses of MCBS.

	Star	Class	Masses of components, $M_\odot$	Remarks
1	EO Aur	*DME*	(11+7); (10-12+6-8); (19.8+19.7); (26.7+26.4); (21.5+21.4); (20.4+20.4)	sometimes there is the photometric wave on light curve
2	V1182 Aql	*SDZ*	(37.8+13.5); (29+11); (75+15); (28+10.7)	
3	V382 Cyg	*KZ*	(37.4+32.8); (26.7+18.9); (26.9+19.0); (10+10)	
4	V599 Aql	*KM*	(18.4+11.5); (10.5+6.5)	
5	UW CMa	*K(E+M)*	(46+34); (23.5+19.3); (29+24); (39.2+29.6); (43.5+32.5)	
6	V367 Cyg	*DM,SD*	(7.6+7.3); (9.6+8.0); (19+12); (2.3+3.6); (1.5+1.3); (13.8+9.7); (8+7)	
7	AO Cas	*SD,K*	(29.2+24.6); (23+18); (29.8+27.8); (23.3+16.8)	
8	DH Cep	*DM,KM*	(42-65+35-54); (23+19); (33.8+28.2)	
9	VV Ori	*DM,KM*	(7.6+3.4); (9.3+4.3); (10.2+4.5); (16.9+5.7); (1.6+1.6)	
10	V505 Mon	*GS*	(13-15+11-12); (50+27)	
11	V453 Sco	*GS*	(22+13); (30+27)	light curve changes
12	RY Sct	*GS*	(39+16); (28+9.5); (49+39); (46+36); (35+11)	light curve changes
13	BM Ori	*?*	(5.3+2.9); (1.5+11.0); (5.5+1.6); (36+9)	light curve changes, main minimum changes
14	Ori	*?*	(12.0+7.6); (18.7+5.3)	

Table 3 MCBS under investigation in Kourovka Astronomical Observatory.

	Star	$m_{\max}$ (filter)	Orbital period, P^d	Observation method
1	CC Cas	7.59 (B)	3.369	Sp, phm, compilation
2	SZ Cas	7.0 (B)	2.698	Sp, phm, speckle, compilation
3	UU Cas	10.4 (p)	8.519	phm, compilation
4	V368 Cas	8.5 (p)	4.452	phm, compilation
5	BH Cen	10.03 (V)	0.792	compilation
6	SV Cen	8.71 (V)	1.658	compilation
7	LY Aur	6.66 (V)	4.002	compilation
8	V701 Sco	8.63 (V)	0.762	compilation

12. *SDE* – semidetached systems evolved from the main sequence;
13. *SDM* – semidetached systems, both components are main sequence stars;
14. *SDZ* – semidetached systems, both components are ZAMS stars.

For the sample of contact MCBS (22 systems in the catalogue) the state of things is similar: peculiarities in the spectrum are revealed for ten MCBS, for six MCBS period changes are detected, evidence of apsidal motion and indications to the third body are found for only two systems, and in four cases the common envelope is discovered.

The stars investigated at the Kourovka Astronomical Observatory are listed in Table 3.

3 SZ Cam

SZ Cam [$m_{\max} = 6.^m99$ (V), $P = 2.^d698$, Sp = O9 IV +B0.5V]. Analysis of observed changes of SZ Cam light curve was carried out in Polushina & Pustylnik (1994) with the use of the model proposed by Pustylnik (1994). The model took into account anisotropy effect of stellar wind on the light curve shape. The anisotropy of stellar wind appears due to periodic variation of gravitational interaction of components invoking the displacement of acoustical point. Since matter density exponentially increases with the chromosphere depth even small displacement of acoustical point may lead to significant variation of matter flow $J = \rho_S \cdot v_S \cdot r_S^2$ taking into consideration its projection to the line connecting component centres. Here v_S is the speed of sound.

The model accounts for the following factors:

- an additional screening of both components radiation that increases depth of both minima especially during the eclipse of the component under accretion;
- the distortion of light curve during minimum of the light and the increase of minimum width;
- the decrease of eclipse amplitude due to the contribution of the envelope luminosity.

So the influence of stellar wind anisotropy deepens and widens the minimum of light curve as well as deforms both descending and ascending branches of minima. This demonstrates the changes of light curve shape with time.

The model uses three free parameters for quantitative estimation of stellar wind effect. These are optical depth, τ, accretion radius $R_{\rm accr}$ and third light, i.e. luminosity of the envelope, $L_{\rm env}$. For explanation of the observed changes of light curve the values of these parameters are as follows: $dM/dt = 1 - 5 \cdot 10^{-7}\ M_\odot$/year, $L_{\rm env} =$ 0.02–0.05, $R_{\rm accr} = 13.4\ R_\odot$, $\tau_2(\phi = \pi) = 0.1$. These conclusions are in agreement with spectral observations performed by Chochol (1980) giving evidence of the presence of circumstellar gaseous structure in the system.

Later the multiplicity was discovered in the system. Visible orbit of third component of SZ Cam was calculated by Gorda using speckle-interferometer observations carried out with 6-meter telescope in SAO (Gorda et al. (2007)). These observations allowed us to localize the depression of light curve near periastron of multiple SZ Cam. Later, studying composition spectrum of this system Gorda found that SZ Cam proved to be quadruplicate system consisting of two similar massive binary systems (Gorda (2008)).

4 CC Cas

CC Cas [$m_{\max} = 7.^m06$ (V), $P = 3.^d368753$, Sp = O9 IV + O9 IV]. There are proofs of strong stellar wind at least for primary components. Conti (1973) notes that He

II λ 4686 lines are as weak (in this star of O9 III spectral type) as it is possible for a supergiant of the same spectral type. However, other signs of high luminosity such as strong lines N III and Si IV indicate III-th luminosity class. It may be star-giant with He II line λ 4686 formed in extended envelope.

Researchers of UV-spectra of O-stars from the analysis of UV resonance lines C IV, N V, Si IV have estimated mass loss rate induced by stellar wind which is equal to $3 \cdot 10^{-7}$ $M_\odot$/year (Howarth, Prinja (1989)). Estimations by Peppel (1984) give the rate of stellar wind by an order of magnitude greater, i.e., $3 \cdot 10^{-6}$ $M_\odot$/year.

The model of CC Cas is constructed by the author using numerous high-accuracy photoelectric observations (Polushina (1985)). The light curve has two solutions. The first with radii ratio of component, k, equal to 0.4 corresponds to the model where massive component fills out its own Roche lobe while the secondary component being MS star of O9–O9.5 spectral type does not fill its own Roche lobe. The second solution demonstrates the opposite situation when the secondary component fills out its own Roche lobe and has luminosity (1^m) and radius (3.5 $R_\odot$) excesses (Polushina (1988)).

Hills et al. (1994) relying on analysis of reticon spectra in the framework of tomography mapping method allowing us to separate blend spectral lines have obtained detached status of the system with low evaluated components.

5 UU Cas

UU Cas [$m_{\max} = 10.^m8$ (p), $P = 8.^d51929$, Sp = B0.5III]. Significant changes of light curve were noted by Polushina (2002). Absolute parameters of the orbit were obtained from the analysis of the light curve uniting the data of observations by Polushina (2002) and by Antokhina & Kumsiashvili (1992). The solution of the united light curve is $M_1 = 34.5 \pm 1.5$ $M_\odot$, $M_2 = 25.7 \pm 0.6$ $M_\odot$, $R_1 = 38.5 \pm 3.1$ $R_\odot$, $R_2 = 24.0 \pm 3.7$, $R_\odot$, $A = 68.97 \pm 0.7$ $R_\odot$.

Let us consider the model of UU Cas corresponding to the given solution:

- The configuration of the system proved to be over-contact.
- The size of the secondary component is varied with the spectral band, for instance, in the U-band the degree of Roche lobe overflow is 10%, while in the V-band the secondary has no time to fill up its Roche lobe as a whole but only by 84%.
- Coefficient of the darkening to the limb is very large that is more likely for red giants.
- Solutions obtained in R- and B-colors are equivalent within the convergence step.
- Value of orbit inclination is changed depending on spectral range and greatly exceeds tolerance interval of 3σ. Similarly, different values of inclination of the orbit obtained in various colors may be explained by the presence of the third light which is generated by the common envelope and is sensitive to the band of observation. For example, for the U-colour the lower boundary of third light, L_3 is one tenth of the summary light of the system.
- The presence of significant residual misalignments of observational and model curves was marked by Polushina (2002).

The fourth issue indicates different conditions of observations of the systems in the first and second half-period. The light of both components is distorted by some circumstellar environment in different ways on different sides of the system. It prompts us to seek separate solutions in the phase intervals of 0–0.5 and 0.5–1 (Polushina, Svechnikov, 2005).

5.1 Features of separate photometric solution

1. Significant difference of the radius of the second component both from the front and backside is noted in all colors. For instance, estimations of backside secondary radius are by 0.12 (semi-axes units) greater in R- and B-colors than the front values. The situation is opposite for U- and V-colors: front radius of the secondary component exceeds its backside radius by 0.06.
2. Primary component also demonstrates discrepancy in radii estimations obtained from different sides.
3. Primary component has very strong limb darkening which is noted in all spectral ranges. In all colors with exception of V-color the secondary component shows coefficient of darkening at the limb close to unity from the side of secondary maximum of light curve that is equivalent to the backside but from the side of primary maximum of light curve the darkening coefficient is close to zero.
4. Duality of values also concerns the estimation of the inclination of the orbit. In U- and V-bands the inclination has maximal value from the side of primary maximum while in B- and R-band the situation is vice versa.

Table 4 Parameters of UU Cas calculated for front and back sides of the orbit.

	UMAXI	UMAXII	BMAXI	BMAXII	VMAXI	VMAXII	RMAXI, RMAXII
k	0.482±0.007	0.468±0.006	0.466±0.021	0.775 0.793 0.900	0.467±0.014	0.425±0.008	0.578±0.051 0.903±0.040
r_2	0.295±0.004	0.238±0.004	0.268±0.009	0.400 0.405 0.434	0.285±0.007	0.228±0.006	0.326±0.017 0.412±0.009
i	66°.46±0.29	75°.96±0.17	70°.33±0.09	62°.90 62°.72 61°.68	68°.91±0.76	73°.55±0.67	67°.56±1.38 62°.36±0.20
x_1	1	0.8	1	1	1	1	1 1
x_2	0.3	0.9	0.0	0.6	1	0	0.1 1
L_1	0.721±0.006	0.908±0.002	0.889±0.007	0.744 0.734 0.679	0.868±0.005	0.905±0.002	0.807±0.025 0.674±0.022
S	11.75	72.11	15.45	61.43 61.50 61.42	43.70	37.25	13.14 11.00

Bisikalo et al. (1997a, 1997b) noted that "results of numerical simulation demonstrate that in stationary regime significant fraction of the common envelope gas approaches the surface of the outflowing star (Roche lobe) in the course of its motion,

and is accreted by this surface, preventing the formation of flows along the stellar surface. Some of the envelope material approaches the donor star and, stripping gas of its surface, participates in the formation of the stream in the vicinity of L_1." Therefore according to the model different mechanisms are started up for intensive accumulation of gaseous matter in the neighborhood of UU Cas primary component leading to a "cocoon"-like formation. In our calculations the sizes of the "cocoon" coincide with the radius of the secondary critical surface Roche. So far as estimations of primary radius in all colors coincide well among themselves as well as with the values of the secondary critical surface size we can conclude that matter of the "cocoon" is optically dense in all UBVR colours.

Later spectral observations of the system by Markov et al. (2010) confirmed the presence of optically dense disc around the secondary component and common envelope covering the system as a whole and expanding with velocity gradient.

Significant deviation of observed light curve from the model may be considered as evidence of a much more complicated structure of gaseous matter in the UU Cam (Polushina (2002)). This deviation exceeds the 2σ-criterion of trustworthiness reaching 0.1 m in some phases. According to data of Polushina (2002) and Antokhina & Kumsiashvili (1992) these O–C residuals of light curve were observed in two seasons separated by 200 orbital periods but well replicating each other. By the method of correlation analysis the cross correlation of O–C residuals in different photometric ranges and for different epochs of observations was found with the high level of significance. The obtained high coefficient of cross-correlation for compared light curves indicates non-random character of the deviation (Polushina (2002)).

As a result of the study of massive early-type CBS the catalogue which includes information about elements of additional variability such as phase interval, amplitudes, and colour indexes was compiled by Polushina and Kumsiashvili (2010).

As a sequel, an analogous study was carried out by Avvakumova (2010a; 2010b) for other contact MCBS systems LY Aur, BH Cen, SV Cen, V701 Sco, for which the additional variability of non-accidental origin was revealed. In these works solutions of light curves are also carried out separately on phases and change of parameters of stars at supervision of systems from different positions and in different spectral intervals is shown.

6 Conclusion

At present, work on the compilation of the catalogue of massive early type MCBS is being continued and as soon as the catalogue data are replenished we hope to generalize the signs of additional variability and to understand its nature.

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