INTERRELATIONS BETWEEN ECLIPSING BINARY SYSTEMS OF VARIOUS TYPES AT THE STAGE OF THE FIRST MASS EXCHANGE

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ABSTRACT. Topics of the empirical study of the evolutionary directions of the eclipsing binary stars of different types are reviewed. It was shown that close binary systems at the first stage of the mass exchange may be distinguished into 3 evolutionary groups, the members of which may evolve from one group to another. This suggestion is justified by the analysis of the dependencies of the main characteristics of the stellar components in binaries and by the location of them at the proposed diagram of the degrees of filling the Roche Lobe.

Key words: Stars: binaries: close, eclipsing; circumstellar matter.

1. Introduction

The stars of binary systems throughout their evolution change the physical and chemical state of their entrails which results in the general characteristics change in the stars. These variations may be expected to tend to the stellar separation into groups from evolutionary status whereas finding relations between the groups enables us to study the laws of binary stellar evolution. With a great variety of absolute characteristics for binary systems, in contrast to single stars, in those there are restrictions of importance caused by the presence of equipotential surfaces, inner critical surfaces, above all – Roche lobes. These can play a part of a lacking criterion permitting to determine evolutionary state of a binary.

Let us consider the problem quoting eclipsing binaries being at the stage of the first matter exchange. We shall refer to these close eclipsing system classified by Svechnikov (1986) as detached in the main sequence (MS– systems), semidetached stars (SD– systems), detached pairs with a subgiant (SD– systems), contact systems of early-type stars (CE– systems) and of W UMa–type (CW– systems), detached stars similar to W UMa-type ($SimCW$– systems) and pairs of AR Lac-type (AR– systems) with rarely are referred to RS CVn–type. Many investigations doubt the reality of DS– system among the above types of binary stars (Budding 1985). It is not clear either whether AR-systems may be attributed to the stage of the first matter exchange.

The investigation of properties of the stars referred to the above types has shown them to consist of either the stars of the main sequence (MS–, CE–, CW–, $SimCW$– systems) or are stars of the main sequence and one subgiant–star (SD–, DS– systems) or the two subgiant stars (AR– systems). Since the stars of subgiant type have evolved earlier than those of the main sequence, whereas masses in stars of AR-systems are low and these evolve very slowly one can affirm that the separation of the above types of binaries into three above mentioned groups is of an evolutionary status of the binaries in the groups and examine their relations and transitions inside and between the groups, above all, in the first group of the system of binary stars.

The evolutionary arrangement of different types of eclipsing binary stars can be carried out from these considerations. As is shown in the estimates of evolutionary tracks for the stars, the latter increase their radii R in virtue of hydrogen burning in the core, variations occurring in effective temperature T and luminosity L generally expressed in absolute bolometric magnitudes M_b. Their motion along the tracks proceeds smoothly and causes no variations in principal dependencies. A marked change in the star's mass M is likely to take place at the contact stage of the evolution. After this phase of "change of parts" for stars of moderate and large masses, to our mind, complicated variations are possible for subgiants only. Constructing such dependencies is the first way of solving our problem.

The second way of clarifying the evolutionary status of different types of eclipsing binary systems is the arrangement of stars according to the stage of filling up their Roche lobes and the study of phenomena concomitant to the process. As investigations have shown, the stars, having filled up Roche lobes, lose matter which is transferred onto the neighboring star and into the surroundings. Matter transfer leads to structure transformation, to variation in angular momentum of a star and stellar system, and therefore to variation in the velocity of a binary system evolution. All this must be shown in the characteristics for stars and in their changes and manifested in variations in binary systems' classifications. And classes of systems are determined well enough, and their variation characterized a certain stage of the star's evolution.

2. Interrelations Between Main Parameters of Stars in Binary Systems

In order to study dependencies of luminosity, radius and temperature of stars upon their masses for different types of eclipsing binary systems, a compiled catalogue (Karetnikov and Andronov 1989) is used containing absolute characteristics for 303 eclipsing binaries. From these data the interrelations are calculated:

$$L_i \propto M_i^\alpha \ , \quad R_i \propto M_i^\beta \ , \quad T_i \propto M_i^\gamma \ , \quad (1)$$

where $i = 1, 2$. Here index $i = 1$ adopted for a more massive star of the pair, whereas i=2 is for a companion star. The magnitudes of L, R, M are expressed in solar units, whereas the effective temperature T in Kelvins. In contrast to a previous publication (Karetnikov 1990), in the given paper there is no separation of systems according to the principle of presence or absence of the orbital period variations.

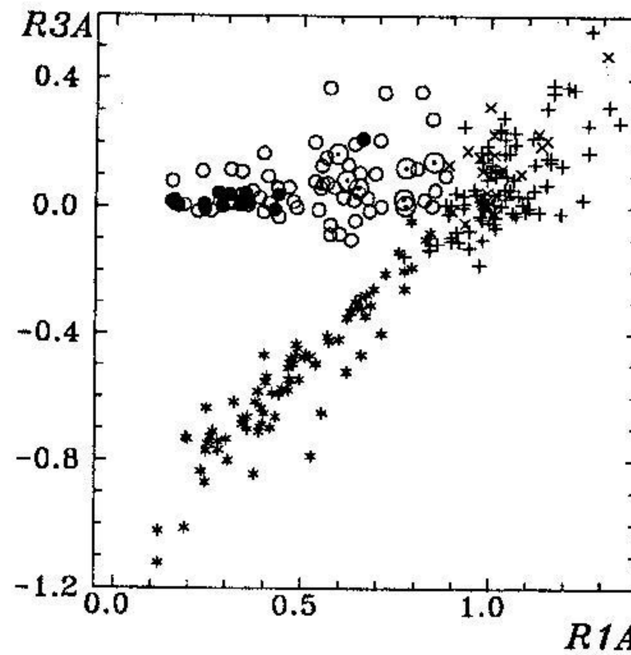

Figure 1: Diagram of filling the Roche lobes for the eclipsing binaries of the types: MS with $M < 1.5M_\odot$ (open circles); MS with $M > 1.5M_\odot$ (filled circles); $SimCW$ ($\odot$); CW ($\times$); CE (+); SD ($*$).

Calculated results of the relations (1) are summarized in Table 1, where designations of $MS1$– form denote a more massive star of the MS– system and the like. The stars in Table 1 are arranged on the principle of decreasing the index α by means of which the star's displacement inside the Main Sequence and beyond it can be described. As it should be expected, initial characteristics of parameters α, β and γ are noticed among the most evolved young companion-stars of the MS– systems and distinctly visualized is the transition from the main sequence stars to the subgiant-stars ($SD2$, $DS2$, $AR1$, $AR2$). The stellar arrangement suggested, in our opining, really reflects the evolutionary sequence but we cannot affirm all the stellar systems to pass consequently all these types of stars.

Now let as consider the problem of filling up

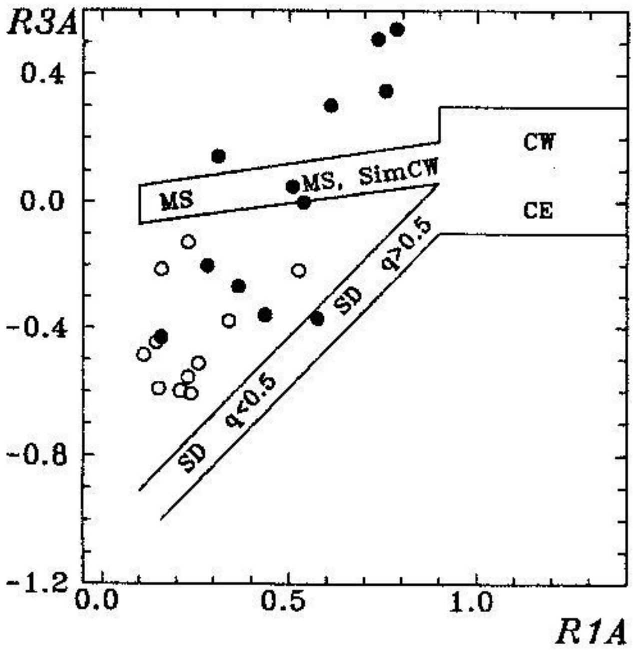

Figure 2: Diagram of filling the Roche lobes for the eclipsing binaries of the types *DS* (open circles) and *AR* (filled circles).

Roche lobes with stars of eclipsing binary systems of different types by using the catalogue (Karetnikov and Andronov 1989) data. We determine the stage of filling up as

$$\begin{aligned} R1A &= R_1/RR_1 \\ R2A &= R_2/RR_2 \\ R3A &= R1A - R2A \end{aligned} \qquad (2)$$

where $R1A$ and $R2A$ are the stages of filling up Roche lobes with more or less massive star of the system respectively, R_1 and R_2 are radii of these stars, whereas RR_1 and RR_2 are radii of Roche lobes calculated from Iben and Tutukov's (1984) formula fitting well in a wide range of the stellar masses

$$RR_i = 0.52\ A\ (M_i/M)^{0.44} \qquad (3)$$

Where A is the distance between stars in solar radii, M_i are the stellar masses, whereas $M = M_1 + M_2$ in masses of the Sun.

The comparison between magnitudes of $R1A$ and $R2A$, which can be called as reduced stellar radii, has shown that the best relative arrangement is illustrated for different types of eclipsing binaries in "$R1A - R3A$"- coordinates. The diagram constructed in the coordinates is represented in Figure 1 where circles mark positions of MS- systems (light circles - with masses $M < 1.5M_\odot$, dark ones - with $M > 1.5M_\odot$), the $\odot$ symbol denotes positions of SimCW- systems, the $\times$ symbol - positions of W UMa-type stars (CW- systems), the + symbol - positions of CE- systems and the asterics - of SD- systems. The disposition of DS- and AR- systems is shown in Figure 2. In Figure 1 are plotted dispositions of 75 MS-systems, 7 systems of $SimCW$-type, 24 CW-systems, 89 CE- systems and 83 SD- systems, all in all 278 eclipsing binary stars.

It is seen from Figure 1 that binary systems consisting of two stars of the main sequence and comprising the first group of the systems provide a sequence which is expressed by a formula (Karetnikov 1987):

$$R3A = -0.02 + 0.17 \cdot R1A \qquad (4)$$
$$\pm.03 \ \pm.05$$

For stars of SD- systems, where a companion is a subgiant-star, one can also observe a steady sequence given by formula (Karetnikov 1987):

$$R3A = -1.11 + 1.20 \cdot R1A \qquad (5)$$
$$\pm.02 \ \pm.05$$

The two above sequences are crossed in the region of contact systems with the values $R1A = 1.05$, $R3A = 0.16$ and represented in Figure 1 with a solid and dash lines respectively.

The proposed sequences are of evolutionary character. Indeed, the stars of MS- systems within their evolution, while proceeding through hydrogen burning in the cores, increase in their sizes, a more massive star attaining this faster. Then reduced stellar radii grow in such a way that both $R1A$ and $R3A$ increase. The growth of these magnitudes may be also due to the evolutionary decrease in the binary system sizes because of angular momentum loss, e.g. in the magnetic stellar wind in low mass stars that will result in the decrease of Roche lobe sizes and increase of relative stellar radii. Hence, the supposition on the evolution of MS- systems along a solid line in Figure 1 from the left to the right reaching the region of contact stars is quite valid.

Table 1.

*	n	α		β		γ	
$MS2$	75	3.78 ± 0.10		0.68 ± 0.03		0.60 ± 0.02	
$MS1$	75	3.78	8	0.69	3	0.57	2
$SimCW2$	7	3.66	73	0.75	10	0.70	18
$SD1$	81	3.50	8	0.71	4	0.48	2
$DS1$	14	3.42	25	0.33	14	0.48	4
$CE1$	89	2.91	11	0.72	3	0.44	2
$CE2$	89	2.67	13	0.67	3	0.42	2
$SD2$	81	2.16	18	0.44	5	0.34	3
$DS2$	14	2.13	38	0.40	21	0.27	8
$CW1$	24	1.62	39	0.53	10	0.17	8
$SimCW1$	7	1.10	11	0.45	6	0.16	5
$CW2$	24	0.98	36	0.35	10	0.04	8

Evolutionary character of the sequence for MS- systems in the diagram "$R1A - R3A$" is confirmed by the stellar separation into groups of low mass and slowly evolved stars (light circles in Fig. 1.) and more massive and faster evolved stars. The group of low mass systems is located in the left part of the sequence with a mean value $R1A = 0.3$ and mass ratio $q = 0.8 - 1.0$, whereas the group of massive systems has mean values $R1A = 0.6$ and $q = 0.1 - 0.8$. It should be noted that limited filling up Roche lobes with low mass systems amounts to $R1A = 0.65$, and with more massive systems - to 0.88. These are likely to be the limits of filling up Roche lobes, within the transition of which the stars of MS- systems change their general characteristics and become systems of other types.

Table 2.

q	$R1A$	n
0.15	0.35	15
0.23	0.44	14
0.27	0.51	16
0.35	0.52	16
0.51	0.62	14

The sequence of SD– systems shown in Figure 1 with dotted lines does not separate the stellar systems from masses. However, with stellar mass ratio q there is such a tendency. According to the statistics with $q < 0.25$ about 80 % of SD– systems have $R1A < 0.50$, and with $q > 0.25$ about 60 % of stars given $R1A > 0.50$. These averaged data are listed in Table 2 and confirm the above said (Karetnikov and Kutsenko 1988). Table 2 can be interpreted as follows: within its evolution a low mass star of SD– system loses matter which partially goes away into space and partially is accreted. This results in a steady decrease of mass ratio q, whereas the increase of accretor's mass leads to the growth of sizes of its Roche lobe and decrease in $R1A$. Thus, evolutionary decrease in q is followed by the decrease in the stage of filling up $R1A$.

3. Proposals for Evolution of Eclipsing Binary Systems

The suggested ways of the systems' evolution can be calculated for low mass MS- systems. With the stellar masses less than 1.5 $M_\odot$, as was shown by Karetnikov (1990ab) due to the magnetic stellar wind these systems lose an angular momentum and we thus have

$$(\dot{P}/P)_{MW} = -6.9 \cdot 10^{-10} \times$$
$$\times \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} \frac{R_1^4 M_1 + R_2^4 M_2}{P^{10/3}} \; 1/\mathrm{yr} \quad (6)$$

The investigation of the formula defines time needed for the variation in the orbital period P_0 to the current P suggestive of invariability in the stellar masses and radii. This time is defined by the formula

$$\Delta t = t - t_0 = -4.3 \cdot 10^8 \times$$
$$\times \frac{M_1 M_2}{(M_1 + M_2)^{1/3}} \frac{P^{10/3} - P_0^{10/3}}{R_1^4 M_1 + R_2^4 M_2} \text{ yr} \quad (7)$$

As is seen from the calculations represented in Table 3, low mass MS– systems of the group with a mean orbital period about 6.12 days can acquire properties of *SimCW*- type stars with an average orbital period equal to 0.72 days in $2 \cdot 10^{10}$ years. This is by one order more time of hydrogen burning in their cores $(3 - 6 \cdot 10^9)$ yrs and transition to subgiants. However, subgiant-stars are not observed in this sequence, that is the above transition appears for the low mass *MS*– stars to be unreal. For the group with an average orbital period near 3.15 days, time $\Delta t = 2 \cdot 10^9$ years that is comparable with the time of hydrogen burning in the core, and these must indicate stellar properties as expanded in case B. With orbital period near 1.58 days, low mass *MS*– systems pass into the region of *SimCW*– systems within $\Delta t = 8.7 \cdot 10^8$ years along the solid line in Figure 1 and then of *CW*– systems within $\Delta t = 3.5 \cdot 10^7$ years remaining main sequence stars.

These arguments can be supported with estimation of period variations due to matter transfer by the stellar wind $(\dot{P}/P)_{SW}$ and the contribution of the magnetic stellar wind $(\dot{P}/P)_{MW}$. Mass transfer by a current mechanism in *MS*– systems is not noticed and therefore it is not taken into account in the given calculation. Table 4 contains calculation results from groups of stars according to their average characteristics as well as total $(\dot{P}/P)$. Magnitudes of matter losses due to the stellar wind are given by a formula (Vilkoviskij and Tambovtseva 1984):

$$\dot{M}_{SW} = 10^{-9.48} \, R_i^2 \, (T_i/10^4\text{K})^4 \, M_\odot/\text{ yr} \quad (8)$$

The estimate of calculation accuracy, with the magnitudes differing by not less than an order, suggests a predominant effect of one of the factors resulting in the orbital period increase, and the consistency of time of its variation with time of hydrogen burning in the core and the stellar system acquiring the properties of stars of another type.

Comparative analysis of the data incorporated in Table 4 is suggestive of the fact that low-mass *MS*– systems of the stars with orbital periods about 1.58 days (*MS*–3) pass the stages of *SimCW*– and *CW*– systems and then merge into one star within time $\Delta t = 5 \cdot 10^5$ years (by using formula (6) and taking $A = R_1 - R_2$ in it). There must be no burnt out core in the single star formed. The group of *MS*–2 systems within the limits of error in calculations has practically no orbital period variations and is likely to pass into the group of *AR*–2 stellar systems. The stars of the group in *MS*–1 system slowly increase in their orbital periods and within hydrogen burning in the cores and transition into the subgiants' stage can pass into the group of binary systems with properties of stars of the *AR*–1 group.

For stars of *CE*– systems the separation is also done from their masses and periods. The suggested separation confirms the separation of the systems into massive, intermediate and low mass groups according to Svechnikov (1986). However, for low–mass objects a more delicate separation is needed taking account of both mass and orbital period of the binary system. The attempt made for such a separation is displayed in Table 5 containing also 3 groups of objects for low mass *CE*– systems. It is seen from the table that low mass CE– systems of stars show variations in their periods similar to *MS*– systems, and some part can be expected to pass into *CW*– systems (*CE*–*a* and the tail *CE*–*b*), and another part is likely to pass into other objects, but this question needs some complementary investigation.

Virtually, our arguments are preliminary and require reliable observational supports. The latter imply the systems of *CW*– stars comprising two groups of stars which must consist of objects close to low–mass *MS*– and *CE*– systems. The separation of *CW*– systems into *A* and *W* groups (Binnendijk 1965) seems to represented the division of these systems but it is not clear whether it supports our hypothesis. Another factor which could be used to strengthen the hypothesis on the transition of

Table 3.

*	n	P	M_1	M_2	A	R_1	R_2	$R1A$	$R2A$
$MS-1$	5	6.12	1.29	1.21	18.96	1.50	1.33	0.20	0.18
$MS-2$	5	3.15	1.34	1.30	12.47	1.69	1.61	0.32	0.34
$MS-3$	5	1.58	1.00	0.90	6.92	1.01	0.92	0.36	0.36
$SimCW$	7	0.72	1.07	0.84	4.14	1.18	0.94	0.72	0.63
CW	18	0.34	1.06	0.55	2.39	1.07	0.69	1.04	0.89
$AR-1$	5	6.80	1.26	1.03	19.83	3.61	3.20	0.45	0.44
$AR-2$	7	3.59	1.40	1.28	13.58	2.82	2.39	0.53	0.47

Table 4.

*	n	P	$\dot{M}_{SW}$	$(\dot{P}/P)_{SW}$	$(\dot{P}/P)_{MW}$	$(\dot{P}/P)$, yr^{-1}
$MS-1$	5	6.12	$2.3\cdot10^{-10}$	$+2\cdot10^{-10}$	$-3\cdot10^{-11}$	$+2\cdot10^{-10}$
$MS-2$	5	3.15	$2.9\cdot10^{-10}$	$+2\cdot10^{-10}$	$-3\cdot10^{-10}$	0
$MS-3$	5	1.58	$1.5\cdot10^{-10}$	$+1\cdot10^{-10}$	$-1\cdot10^{-9}$	$-1\cdot10^{-9}$
$SimCW$	7	0.72	$0.8\cdot10^{-10}$	$+1\cdot10^{-10}$	$-1\cdot10^{-8}$	$-1\cdot10^{-8}$
CW	18	0.34	$0.8\cdot10^{-10}$	$+1\cdot10^{-10}$	$-1\cdot10^{-7}$	$-1\cdot10^{-7}$
$AR-1$	5	6.80	$5.7\cdot10^{-10}$	$+4\cdot10^{-10}$	$-4\cdot10^{-10}$	0
$AR-2$	7	3.59	$9.5\cdot10^{-10}$	$+8\cdot10^{-10}$	$-9\cdot10^{-10}$	$-1\cdot10^{-10}$

low mass stars to $CW-$ systems is an observed peculiarity of $CW-$ systems as multiple stars. As Istomin (1987) has shown, 80 % of these systems are multiple. Then it is necessary to search for multiplicity in low mass MS–3 and CE–a systems. This work is being carried out by our researchers.

Analogous research work on other types of eclipsing binary stars (SD–, DS– systems) is rather unreliable due to scanty knowledge of current processes occurring there, particularly, of matter transfer and its accretion, and also due to a subgiant star present in the systems showing a complicated track in the "spectrum–luminosity" diagram. This is not favored by the stellar separation into groups of AO Cas- type (massive pairs), of β Per– type (normal pairs), eclipsing systems with "a double contact" (Pustylnik 1989), as well as systems with a small ratio of masses of R CMa–type. Until the problem of numerical determination of matter transfer in eclipsing binaries of SD- and DS- systems is solved, the calculations of their evolution can be of scenery character only. Thus, the problem of empirical determination of evolution in these systems is to be solved.

Location of sequences of the DS– and AR– systems is illustrated by Fig.2. Analysis of Fig.2. shows that the DS– systems are located similar to the SD– systems. However, the unsufficient knowledge of the absolute characteristics does not allow to discuss the observed sequence surely. Calculations of $(\dot{P}/P)$ argue for a general increase of the orbital periods of these systems. The location of the AR– systems arizing near the region of the degree of filling the Roche lobe by the massive MS– systems at $R1A = 0.5 - 0.6$ indirectly argue for a suggestion that the AR– systems evolved from the low–mass MS– systems with large orbital periods. In this case, as one may see from Tables 3,4, the safety of the mass of the stars in a pair, as well as the period increase up to observed values, and as the transition of the stars to a subgiant stage.

Our empirical studies, in general, confirm theoretical scenaria by different authors, which are sufficiently good described by Masevich and Tutukov (1988) and other articles. However, in this paper we tried to describe the works on detailization of the evolutionary directions of separate types of the eclipsing binaries and on interrelations between these types. It seems to us, that the shown results confirm:

1) the idea of the transitions from one type of the eclipsing binary stars into another;

2) the binarity of the "contact" evolutionary stage of the systems, at which a part of the stars finishes its way as the binary stars (low-mass, short-period $MS-$, $SimCW-$, $CW-$, $CE-$ systems of stars), merging into one object; the rest evolving to other types of the eclipsing binary stars with the formation of subgiant stars.

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ON ESTIMATES OF LOWER AND UPPER LIMITS FOR THE MASSES OF COMPACT COMPONENTS IN CLOSE BINARIES

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ABSTRACT. A method of the determination of limits for a compact component mass on the base of disk emission lines parameters is described. Lower limit of mass depends upon the distance between maxima in double peaked lines, upper upon full width of line. The method is tested for some cataclysmic variables with well-known masses of compact components. It is obtained a lower limit for the mass of the compact object in the close binary SS 433 is $4.9M_{\odot}$. This component apparently is a black hole.

Key words: Stars: Binaries, Accretion Disks