EVOLUTIONARY EFFECTS IN CLOSE BINARIES: ANALYSIS OF THE DISTRIBUTION OF ORBITAL ECCENTRICITIES

A.M.Cherepashchuk[1], V.G.Karetnikov[2]

[1]Sternberg Astronomical Institute (SAI), Moscow, Russia
[2]Astronomical Observatory of Odessa National University (AO ONU), Odessa, Ukraine

ABSTRACT. Depencencies of orbital eccentricity e on orbital periods P in close binary systems (CBS) of different masses and ages, being at the Main Sequence (DMS) and being eclipsing binary stars (EBS), are reviewed. The EBS groups of similar age are separated into objects with convective (A-M - stars) and radiative (O-B - stars) envelopes, and into the group of massive stars.

It has been found, that the value of e always increases with increasing P and decreases with relative radius of the main star of EBS. In all groups of stars, the transition period $P_{tr} \sim 3^{\rm d}$: for $P < 3^{\rm d}$, $e = 0$, for $P > 3^{\rm d}$, $e \neq 0$. As for the majority of semi-detached stars (SDS), $P < 2^{\rm d}$, it is possible to assume, that the circularization of their orbits took place at the DMS stage.

The comparison of dependencies of orbital eccentricities on orbital periods in EBS and WR+O systems has shown distinction in the values of P_{tr} ($3^{\rm d}$ and $14^{\rm d}$, respectively), that specifies difference in mechanisms of orbital circularization in these types of binary stars.

Key words: Stars: Close binary: Eccentricity: Evolution.

1. The relation between orbital eccentricities and periods, $e(P)$, for Close Binary Systems (CBS)provides important information on energy dissipation mechanisms of orbital motion in CBS as well as on their evolutionary status (see, for example, Zahn, 1977; Koch and Hrivnak, 1981; Zahn, 1989). The most perspective and non-ambiguous are studies of orbital eccentricity distributions or similarly aged CBS, for instance, belonging to the same cluster (Cherepashchuk and Karetnikov, 2003; Mayor and Mermillard, 1984). Orbital elements derived from observations of CBS are, however, quite sparse. As a matter of fact, the largest amount of information on elements of CBS is available for the objects which do not belong to stellar clusters.

Let us consider the question for one CBS type: eclipsed binary systems, i.e. the objects at the first stage of their mass exchange process. According to Svechnikov's (1986) classification, there are seven subtypes among eclipsed binaries depending on stellar and binary parameters, their ages, and durations of their evolutionary stages. These objects were shown to pass from one subtype to another in the process of their evolution, their parameters and evolutionary status being changed. Circularization of their orbits was considered until recently to be due to only matter and angular momentum transfer (Paczynski, 1971). Indeed, all known semi-detached systems containing a main-sequence massive star along with a low-massive subgiant have circular orbits, the fact was believed to result from the mass exchange in CBS. The mass exchange in CBS, until recently, was assumed to begin when approaching a contact stage and to yield circularization of an orbit. As semi-detached systems with subgiants were certain to have passed the stage of mass exchange, all known systems of that type seemed to have circular orbits and, hence, no numerical estimates of their eccentricities had been made.

Recently new observational evidence and theoretical considerations have appeared which render this "indisputable" statement rather dubious. First of all, distribution of orbital eccentricities of CBS in stellar clusters of different ages has been analyzed and the value of transition period, P_{tr}, has been shown to be equal to $P_{tr} \approx 12$ days for CBS with the age $T \approx 10^9$ years (the transition period corresponds to the transition from a circular orbit to an elliptical one). The conclusion first derived in our pioneering work indicates that a vast majority of known semi-detached systems managed to attain circular orbits at a detached main-sequence stage due to dissipation of energy of their orbital motion because of static tidal effects in stars with convective envelopes.

Thus, according to our results published by Cherepashchuk and Karetnikov (2003), the mass exchange in most known semi-detached systems occured while in circular orbits, the role of mass exchange in circularization of their orbits being insignificant. Circularization of an orbit during the mass exchange oc-

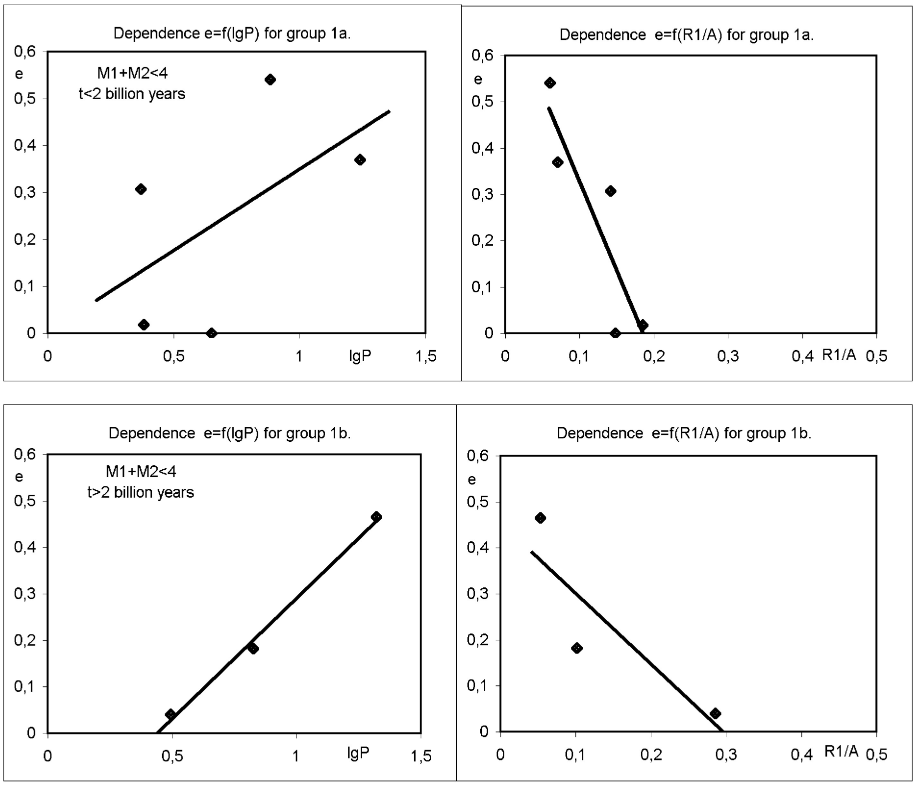
Dependence e=f(lgP) for group 1a.
M1+M2<4
t<2 billion years
Dependence e=f(R1/A) for group 1a.
Dependence e=f(lgP) for group 1b.
M1+M2<4
t>2 billion years
Dependence e=f(R1/A) for group 1b.
e
0
0,1
0,2
0,3
0,4
0,5
0,6
0,5
1
lgP
1,5
R1/A

Fig. 1.

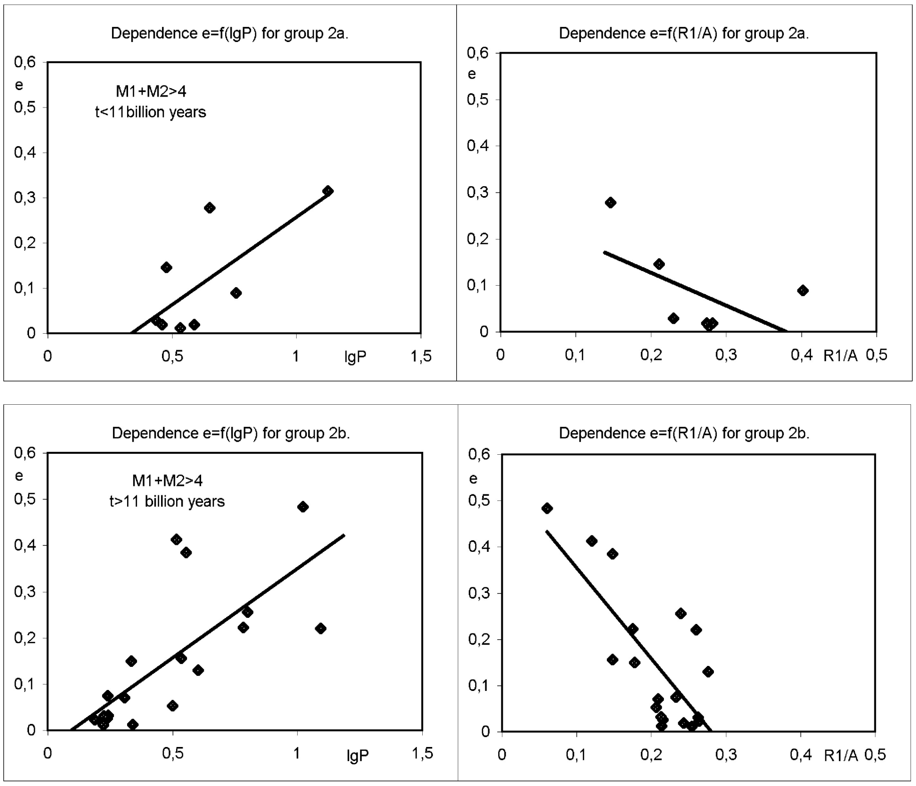
Dependence e=f(lgP) for group 2a.
M1+M2>4
t<11billion years
Dependence e=f(R1/A) for group 2a.
Dependence e=f(lgP) for group 2b.
M1+M2>4
t>11 billion years
Dependence e=f(R1/A) for group 2b.
e
0
0,1
0,2
0,3
0,4
0,5
0,6
0,5
1
lgP
1,5
R1/A

Fig. 2.

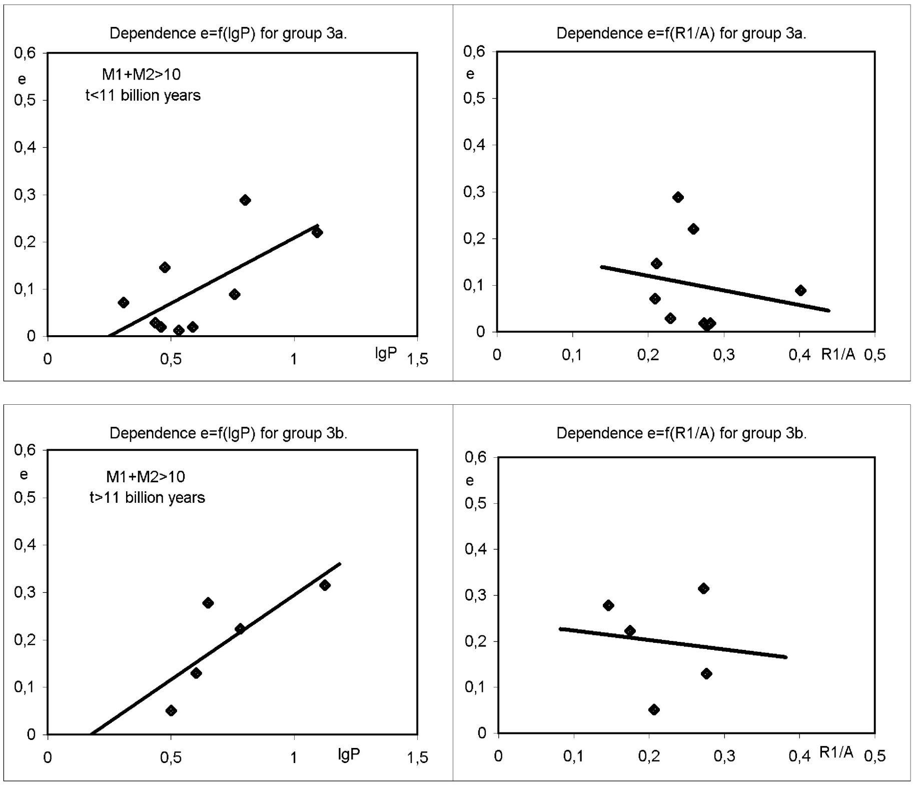

Fig. 3.

curs as follows: matter transfer from a more massive star to a low-mass star yields decreasing both eccentricity and a semi-major axis. To the contrary, at the second stage of mass exchange when matter flows from the low-mass star to a more massive companion, the semi-major axis of the orbit grows and so does, as a rule, its eccentricity.

Circularization depends strongly on parameters of the stars forming a pair. Massive CBS have mass exchange time scales which are very short and close to the thermal scale of a massive star, $T_k \approx 10^7/M_1^2$, and originally elliptical orbits can hardly get circular during the initial stage of mass exchange. The subsequent transfer of matter from the low-mass star to its more massive companion increases the residual orbital eccentricity. We have indicated earlier that this mechanism can account for considerable orbital eccentricities in WR+O binaries with great ($P > 14^d$) orbital periods.

Masses of CBS companions affect the structure of external stellar envelopes, convective and radiative envelopes displaying different effects. Periods P_{tr} of CBS involving stars with convective envelopes depend strongly on their ages. For the CBS in the young Hyades cluster (the age is $T \approx 6 \cdot 10^8$ years) $P_{tr} = 5.6$ days, for the CBS in the old M67 cluster ($T = 5 \cdot 10^9$ years) $P_{tr} = 12.4$ days, and for the CBS from the galactic galo ($T = 1.5 \cdot 10^{10}$ years) $P_{tr} = 18.7$ days. If CBS do not belong to a cluster or belong to different-aged clusters, relation $e(P)$ should be interpreted taking into account difference in ages.

There appears another problem when researching CBS. The matter is, orbital eccentricities of eclipsing binary stars are determined from light-curve solutions and radial velocity curves. "Photometric" (e_{ph}) and "Spectral" (e_{sp}) eccentricities of an orbit, however, can differ because of gas streams flowing in interacting CBS. The most critical to the gas stream structures are eccentricities derived from radial velocity curves. Thus only eccentricities determined with the use of photometric observations are fit to the analysis of orbital eccentricity distribution.

This work studies distribution $e(P)$ for the CBS containing two Detached Main-Sequence (DMS) stars which display eclipses and for which reliable relative radii, R_1/A and R_2/A ($R_{1,2}$ being the radii of binary components, A the major semi-axis of an orbit), photometric orbital eccentricities e_{ph} and, in some cases, bolometric luminosities of the stars L_{bol} are available. The most reliable values for the relative radii and eccentricities e_{ph} have been found for eclipsing CBS with apsidal rotation which were studied by Khaliullin (1997).

Stellar and system parameters are available from observations for a large number of eclipsing binaries, a hundred of DMS systems having determinations of their age (Dryomova and Svechnikov, 2003). All objects for which the ages and star parameters are known can be divided into groups having almost the same age.

For every group of stars relation $e(P)$ or, more strictly, $e(R_l/A)$ can be derived. Since a typical time of orbit circularization is an unequivocal power function of (R/A) with a great index of power (8.5 for the CBS with convective envelopes and 10.5 for the CBS with radiative ones, Zahn (1977)), the star of a larger radius plays the most critical role in orbit circularization.

2. This work is intended to single out groups of eclipsing DMS systems of equal age and to investigate relations $e(R_l/A)$, $e(P)$ in order to better investigate energy dissipation mechanisms of orbital motion of CBS components. The eclipsing binaries containing stars both with convective (A-M type stars) and radiative envelopes (O-B type stars) are to be considered. The results obtained can be used to check theoretical relations between ages T and transition periods P_{tr}. Theoretical considerations indicate that the age T of CBS with convective envelopes is a power function of P_{tr}: $P \sim P_{tr}^n$, where $n \approx 3 - 5$.

We have used the stellar data from our earlier works along with eccentricities obtained by Khaliullin (1997) and ages of stars calculated by Dryomova and Svechnikov (2003) and Kovaleva (2001). Only eclipsing binary stars belonging to DMS type have been used, altogether 49 CBS. All objects are divided into three groups: 1) stars with convective envelopes (the mass of the star system is supposed to be less than 4 solar masses), 2) stars with radiative envelopes (the mass of the star system is supposed to be more than 4 solar masses), and 3) star systems having masses over 10 solar masses.

The most young objects from group 3 (14 stars) have evolutionary age between 3 and 48 millions of years, the stars from group 2 (27 stars) have age between 4 and 2460 millions of years, and low-mass stars from group 1 (8 objects) have age between 670 and 8320 millions of years. Subgroups in these groups have been singled out depending on their age. Because of few number of objects with "photometric" eccentricities e_{ph} available (low-mass CBS are rather poorly investigated), only two subgroups could be singled out in each group. Group 1 has the division limit near 2000 million years, group 2, near 50 million years, and group 3, near 11 million years.

Relations $e(P)$ and $e(R_l/a)$ are constructed for all groups of CBS under investigation (see below). The parameters and the limit age of systems are indicated. To obtain these data our previous findings have been used that were published by Cherepashchuk and Karetnikov (2003).

While scrutinizing the plots the following conclusions can be derived:

- orbital eccentricity of DMS eclipsing binaries grows proportionally to their orbital periods and decreases as a relative size of the main star, R_l/A, increases (which determines the corresponding Roche lobe filling factor);
- for "young" stars with convective envelopes (subgroup 1a) eccentricity approaches zero if a binary system is very close and Roche lobe filling factor is only $R_l/A \sim 0.2$, while in case of "older" objects eccentricity becomes zero already for all CBS with periods less than 3 days and Roche lobe filling factors $R_l/A \sim 0.3$;
- stars with radiative envelopes have eccentrical orbits ($e \neq 0$) if their orbital periods exceed 3 days, and in case of $e = 0$ Roche lobe filling factor for the main star is close to 0.3. In other cases eccentricity grows rapidly with decreasing R_l/A;
- CBS with total mass more than 10 solar masses also have eccentrical orbits if their orbital periods are more than 3 days, the conclusion being in agreement with the earlier findings concerning OB+OB stars (Cherepashuk and Karetnikov, 2003); the Roche lobe filling factor is hard to estimate;
- transition periods for DMS stars and WR+O systems differ what implies different orbital circularization mechanisms. The transition period for WR+O systems is about 14 days;
- there is a good coincidence between observations and theoretical considerations by Zahn et al.(1989). Theory predicts that $(R_l/\Phi)_{tr} \sim 0.25$ for stars with convective envelopes, that is, for star systems with the total mass more than 4 solar masses;
- DMS systems having orbital periods $P < 2$ days and zero eccentricity ($e = 0$) are likely to have completed circularization of their orbits. Most semi-detached systems are supposed to acquire circular orbits when they were at the DMS stage.

The results obtained are preliminary. The search for additional statistical information is under way.

References:

Cherepashchuk A.M., Karetnikov V.G.: 2003, *Astron. Zh.*, **80**, 46.

Dryomova G.N., Svechnikov M.A.: 2003, *Ap.Space Sci.*, **283**, 309.

Khaliullin Kh.F.: 1997, *in book Binary Stellar Systems, ed. A.G.Massevitch*, Moscow, Kosmosinform, 154.

Koch R.H., Hrivnak B.J.: 1981, *Astron. J.*, **86**, 438.

Kovaleva D.A.: 2001, *Astron. Zh.*, **78**, 1104.

Mayor M., Mermillard J.C.: 1984, *in Observational Tests of the Stellar Evolution Theory, eds A.Maeder, and A.Renzini, IAU Symp.*, 105, Dordrecht, Reidel, 411.

Paczynski B.: 1971, *Ann. Rev. As. Ap.*, **9**, 183.

Svechnikov M.A.: 1986, *Catalog of Orbital Elements, Masses and Luminocities of Close Binary Stars*, Irkutsk, 225.

Torres G., Latham D.W. et al.: 1992, *in Evolutionary Processes in Interacting Binary Srars, eds. Y.Kondo, R.Sistero, R.S.Polidan, IAU Symp.*, 151, Dordrecht, Reidel, 491.

Zahn J.P.: 1977, *As. Ap.*, **67**, 162.

Zahn J.P.: 1989, *As. Ap.*, **220**, 112.

Zahn J.P., Bouchet L.: 1989, *As. Ap.*, **223**, 112.