THE FORMATION AND EVOLUTION OF LOW-MASS CLOSE BINARIES WITH COMPACT COMPONENTS

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ABSTRACT. We discuss the formation and evolution of interacting low-mass close binaries with a He-1CO- or ONe-dwarf neutron star or a black hole as a compact component. Mass exchange leads to cataclysmic events in such systems. The rate of semidetached low-mass close binary formation is $5x10^{-3}$ yr^{-1} if the accreting component is a He degenerate dwarf, $5x10^{-3}$ yr^{-1} if it is a CO-dwarf and $3x10^{-8}$ yr^{-1} if it is a neutron star. Systems with compact accretors arise as the result of the common envelope phase of close binary evolution or due to collisions of single neutron stars or dwarfs with low-mass single stars in dense stellar clusters. Evolution of LMCB to the contact phase in semi-detached stages is determined mainly by the angular momentum losses by a magnetic stellar wind and radiation of gravitational waves. Numerical computations of evolution with momentum loss explain observed mass exchange rates in such systems, the absence of cataclysmic variables with orbital periods 2^h-3^h, the low number and the evolutionary status of systems with orbital periods shorter than 80^m. In conclusion we list unsolved problems related to magnetic stellar wind, the distribution of young close binaries over main initial parameters, stability of mass exchange.

1. INTRODUCTION

This review is mainly devoted to the study of the origin of cataclysmic and low mass X-ray binaries and their evolution, which is governed by angular momentum loss (AML) by the magnetic stellar wind (MSW) and gravitational wave radiation (GWR). The standard model presents a low-mass secondary filling its Roche lobe (donor) and a compact accreting primary, which can be a helium, carbon-oxygen or oxygen-neon degenerate dwarf in cataclysmic variables or a

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neutron star or possibly a black hole in X-ray binaries. The mass of the donor is usually lower than the mass of the accretor. According to observations, the donor is, as a rule, a low-mass main-sequence star, but sometimes it can be a subgiant (Cyg X-2), a giant (TCrB) or a helium degenerate dwarf (GP Com). According to theoretical arguments, it is possible that the donor may be as well a helium star, a carbon-oxygen dwarf, a heavy disk surrounding the compact component, or even a dense interstellar gas cloud slowly moving relative to the neutron star (Tutukov and Yungelson, 1986).

The mass exchange in systems under consideration is usually accompanied by eruptive phenomena of different kinds. The main feature of these instabilities is accumulation of some critical mass of exchangeable matter in the accretion disk, envelope of a compact star or in the accretor itself before transition of this matter into a new state. Iben and Tutukov (1984) named them accumulation instabilities. They are: a recurrent accumulation of matter in the accretion disk (a dwarf and, possibly, some recurrent optical and X-ray novae; Osaki (1974), a recurrent accumulation of thermonuclear fuel in the degenerate envelope of degenerate dwarfs and neutron stars (classical and recurrent novae; Gurevich and Lebedinskij (1947)), X-ray bursters (Maraschi and Cavaliere (1977)), and, finally, nuclear explosion of He-, CO- or ONe-degenerate dwarfs exceeding some critical mass (possibly supernovae of Type 1, Whelan and Iben, 1973), or the transformation of a neutron star into a black hole. Eruptive activity may be also caused by an unstable outflow of matter from the donor (Bath, 1975; Edwards, 1985).

The conservation law gives a simple equation which relates the number of bursts per year in the Galaxy N with the frequency of formation of the corresponding systems ν, the average mass of the secondary M_2 and the critical mass of accumulated matter M_{C2}:

$$N = \nu M_2/M_{C2}. \qquad (1)$$

There is a reasonable agreement between this simple relation and observations of a dwarf and a classical nova, X-ray bursters and recurrent X-ray novae (Iben and Tutukov, 1984; Tutukov and Yungelson, 1985).

It is quite possible that the list of accumulative instabilities in low-mass binaries is not completed by the relatively simple examples described above. Apart from that, it is worth to point out that a part of already mentioned instabilities can also operate in other binaries. E.g. the unstable accretion and thermonuclear activity of accreting dwarfs may manifest themselves in symbiotic binaries. The unstable accretion by a single young star can explain flashes of FU Ori-type stars. Even in single stars accumulation of the helium shell in the double shell burning asymptotic giant branch star leads to recurrent shell helium flashes.

We can name now at least three circumstances that helped to progress in our understanding of the nature and evolution of low-mass interacting binaries. The first is the stimulating role of the discovery of low-mass X-ray binaries. The second is the realization of the role of common envelopes in the evolution of possibly most wide binaries with convective envelopes or mass ratios of components far from 1 (Paczynski, 1976; Meyer and Meyer-Hoffmeister, 1979). The third circumstance is a quantitative approach to the problem of AML by a MSW and by GWR. The general evolutionary scenario of close binaries with components of moderate mass ($M \lesssim 10\ M_\odot$) has been developed as a result (Tutukov and Yungelson, 1981; Tutukov, 1981; Yungelson and Massevitch, 1983; Iben and Tutukov, 1984; Paczynski, 1984; Webbink, 1985). The scenario approach appeared to be an efficient means of investigation of the most general properties of evolving close binaries. It shows the origin and connections of many astrophysical phenomena and objects: cataclysmic binaries, algols, WUMa stars, barium stars, supernovae, helium stars, low-mass X-ray binaries and many others (Tutukov and Yungelson, 1986; Iben and Tutukov, 1986).

2. MAIN DRIVING FORCES OF THE EVOLUTION OF LOW-MASS CLOSE BINARIES

A quantitative theory of formation of close binaries is absent. Therefore, in particular, it remains unknown what determines the distributions of binaries over masses and mass ratios of components and semimajor axes and how these distributions are determined. The statistical analysis of the data in catalogues of spectroscopic, eclisping and visual binaries provides after allowing for selection effects, an empirical function for the binary star formation rate in solar vicinity. Extending of this function over the whole Galaxy provides us with the following expression for the birth rate of binaries:

$$d3\nu \approx 0.2\ d\lg a \cdot f(q_o) dq_o \cdot M^{-2.5}\ dM\ yr^{-1}, \qquad (2)$$

where $f(q_o)$ is the initial distribution of binaries over the mass ratio of components ($\int_0^1 f(q_o) dq_o = 1$), a is the semimajor axis, M is the mass of primary star (Popova et al., 1982). The most poorly known parameter is $f(q_o)$. We assume here, following Iben and Tutukov (1985) that $f(q_o)=1$. If we add now to Equation (2) lifetimes of binaries in different evolutionary stages, we can estimate the total number of corresponding systems in the Galaxy. The scenario of evolution of a close binary with components of moderate masses is shown in Figure 1. One can find a detailed description of the scenario in the review by Tutukov and Yungelson (1986).

The formation and evolution of most cataclysmic systems are presented by the right-hand branch of Figure 1. To find initial parameters of binaries evolving into cataclysmic systems one needs to know how these parameters transform in the course of the mass exchange. In order to form a degenerate component the initial system has to be wide enough. Mass exchange in such systems starts usually in the thermal or even in the dynamical time scale of the donor

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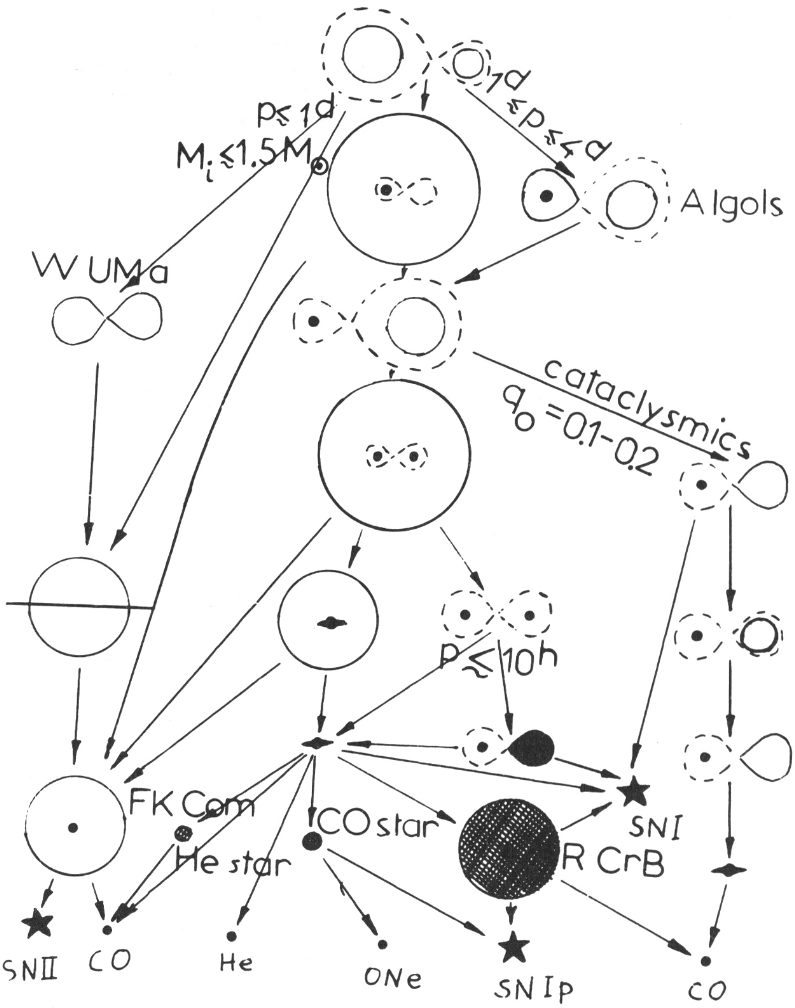

Figure 1. Evolutionary scenario for low-mass close binaries ($M_2<M_1\lesssim10M_\odot$, Tutukov and Yungelson, 1986). Rings are surfaces of unevolved stars, dots are degenerate cores or dwarfs. Dashed lines mark Roche lobes, if they do not coincide with stellar surfaces. Bars denote heavy disks, stars denote supernovae. He or CO nondegenerate stars or envelopes are cross-hatched. Common envelopes are shown as rings encircling the whole system. Arrows indicate possible evolutionary transitions.

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star. As a rule, this leads to the formation of a shortly living common envelope around the system. Since the mass of the accreting star cannot be changed significantly during the common envelope phase, the semimajor axis of the binary after this phase can be found from simple energy considerations (Tutukov and Yungelson, 1979):

$$\beta M_2 M_{wd}/a_f = M_1{}^2/a_o, \tag{3}$$

where M_1 and M_2 are the initial masses of the components $(M_2<M_1) M_{WD}$ is the mass of the degenerate core of donor at the moment of Roche lobe overflow, a_o and a_f are the initial and the final semimajor axes of the system, β is the efficiency of the expenditure of the orbital energy on the common envelope dispersion. We assume here for numerical estimates that $\beta = 1$ and $M_2 \approx 0.67\ M_{WD}$ as a condition for the slow mass exchange during the second semidetached stage (Tutukov et al., 1982).

Thus, after the common envelope phase we get a system containing a degenerate dwarf and a low-mass main-sequence star (Figure 1). Masses of secondaries in cataclysmic binaries as a rule, are lower than $\sim 0.8\ M_\odot$, therefore the thermonuclear burning cannot be the main driving force of their evolution. Kraft et al. (1982) proposed the GWR as a possible moving force of the evolution for cataclysmic binaries. The time scale for drawing into contact components of a detached binary is

$$\tau_{RGW} \approx 7.7\text{x}10^7\ (M_1 + M_2)^{1/3}\ M_1{}^{-1}\ M_2{}^{-1} P^{8/3}\ \text{yr} \tag{4}$$

where M_1 and M_2 are the masses of the components in solar units, P is the orbital period in hours. It is evident that GWR will draw into contact components of all binaries of solar mass in cosmological time if the initial separation is less than $\sim 3\ R_\odot$. After the Roche lobe overflow GWR will keep the system in a semidetached state with the mass exchange rate $\sim 10^{-10} M_\odot\, \text{yr}^{-1}$. However, mass exchange rates for most cataclysmic binaries significantly (up to hundred times) exceed those supported by the GWR (Tutukov and Yungelson, 1979). To explain observed mass exchange rates Verbunt and Zwaan (1981) assumed that nondegenerate components have a standard magnetic stellar wind (MSW). This is the same wind which is responsible for the braking of rotation of late spectral type stars in accordance with the empirical law: $v_e \approx 1.78\text{x}10^5\ \alpha\ t^{-0.5}$ km s^{-1} (Skumanich, 1972), where t is the age of a star in 10^6 yr, v_e is the equatorial velocity of rotation of the star, α is a dimensionless parameter which is close to unity. The quantitative expression for the rate of angular momentum loss is (e.g. Tutukov, 1983).

$$\frac{\dot{J}}{J} = -10^{-14}\ \frac{R_2^4 (M_1+M_2)^2}{\alpha^2 a^5 M_1}\ \ s^{-1}, \tag{5}$$

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where M_1 and M_2 are the masses of the components in solar units and R_2 is the radius of the donor. Equation (5) was successfully applied to the study of the evolution of cataclysmic binaries, WUMa-stars, low-mass X-ray binaries, algols (Rappaport et al., 1983; Taam, 1983; Iben and Tutukov, 1984a; Verbunt, 1984; Patterson, 1984; Tutukov et al., 1985; Kraicheva et al., 1986). The necessity to explain the 2^h - 3^h *gap in the distribution of cataclysmic variables over orbital* periods forces to assume that MSW becomes unefficient for completely convective secondaries ($M_2 \lesssim 0.3\ M_\odot$, see Section 4). The time scale of drawing components together is:

$$\tau = \left| \frac{J}{\dot{J}} \right| = \frac{3 \times 10^6 \alpha^2 M_1 a^5}{R_2^4 (M_1 + M_2)^2} \quad \text{yrs.} \tag{6}$$

All values in Equation (6) are in solar units. The integration of Equation (6) shows that all detached systems with a $\lesssim 12 M_1$ ($0.3 \lesssim M_1/M_\odot \lesssim 1$) succeed to become in the cosmological semi-detached ones. It is evident that MSW has a larger zone of 'capture' than the GWR, therefore it is necessary to take it into account in the study of all evolutionary low mass binaries. It is important to point out that although Equation (5) with standard $\alpha \approx 1$ is enough to fit observed mass exchange rates in all above mentioned binaries, it still remains unclear whether this extrapolation of empirical data for single stars to binaries is justified.

3. THE ORIGIN AND EVOLUTION OF CATACLYSMIC BINARY STARS

Now we turn to the discussion of the formation of cataclysmic binaries. The evolution of the precataclysmic system before the formation of a degenerate dwarf follows the main branch of the scenario (Figure 1).

The chemistry of the white dwarf primary depends on its initial mass and semimajor axis of the orbit. Primaries with M_1, $\lesssim 2.3\ M_\odot$, a $\lesssim 500\ R_\odot$ produce He-dwarfs, all other primaries with $M \lesssim 8\ M_\odot$ produce CO-dwarfs. It is possible that 8-10 $M_\odot$ primaries under certain conditions produce ONe-dwarfs instead of CO-dwarfs (Iben and Tutukov, 1985).

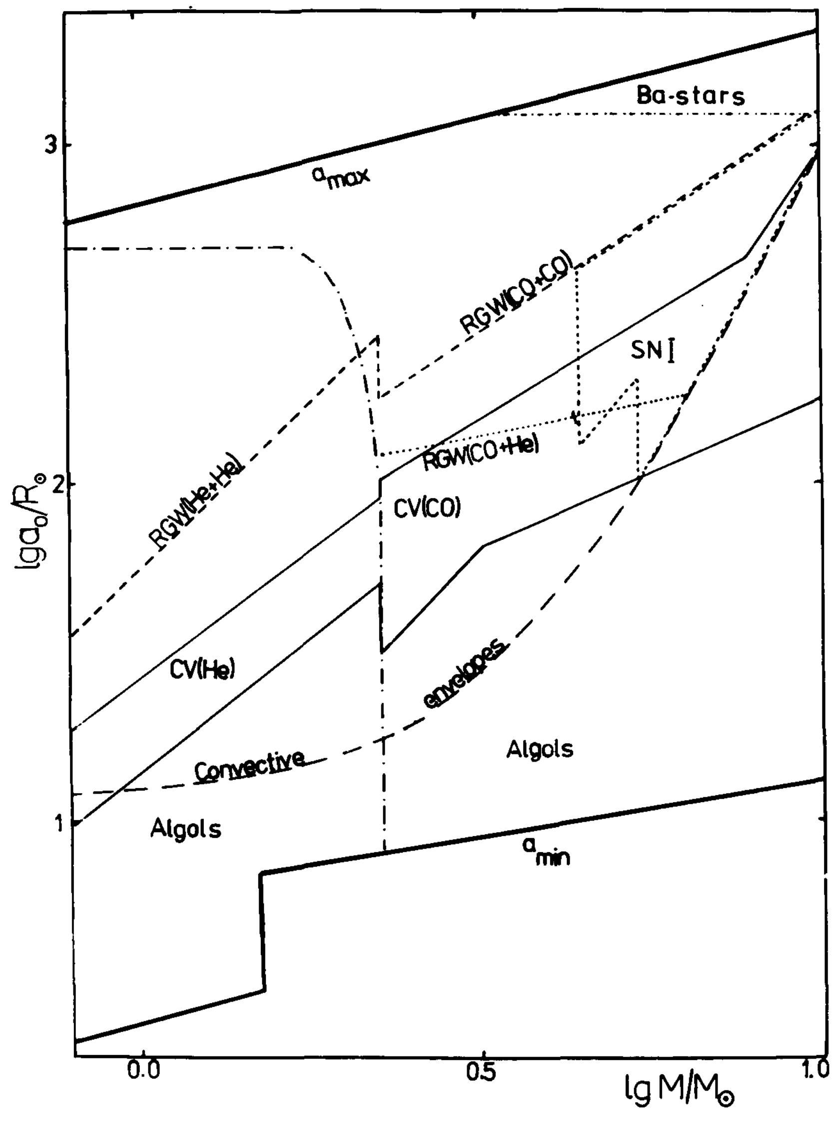

Figure 2. Positions of progenitors of cataclysmic variables (C V, thin continuous lines) with helium (He) or carbon-oxygen (CO) accretors, algols, supernovae of type I (SN I), and barium (Ba) stars in the initial mass of primary - initial semimajor axis diagram. a_{min} is the minimal semimajor axis of binaries. a_{max} is the maximal semimajor axis of binaries which become semidetached. The lower dashed line is the border of deep convective envelopes for primaries filling their Roche lobes. The higher is the border of systems in which the degenerate remnants of components merge due to RGW in the cosmological time. The dotted line RGW (CO+He) limits the position of systems in which He-stars merge with CO-dwarfs in the time scale of He-burning. Dashed-dotted line is the border between systems producing He- or CO-dwarfs.

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In Figure 2 we show the position of progenitors of cataclysmic binaries in the M_1–a plane. To draw together the white dwarf and the low-mass secondary is possible only inside a common envelope. Common envelopes are formed only in systems with primaries with deep convective envelopes or with a high initial mass ratio of the components.

Numerical results of Iben and Tutukov (1985) allow to estimate masses of white dwarfs after a common envelope stage: $M_{wd}/M_\odot \approx 0.1 (a/R_\odot)^{0.25}$ if $M_1 \lesssim 2.3$ $M_\odot$ and $M_{wd} \approx 0.13$ M_1 for $M_1 > 2.3$ $M_\odot$. The initial mass ratio of the components q_o has to be low enough to allow a mass exchange in the time scale of AML by a MSW or GRW. This is possible only if $M_2 \lesssim 1.2$ M_{wd} for $0.8 \lesssim M_2/M_\odot \lesssim 1.5$ and if M2$\lesssim 0.67$ M_{wd} for $M_2 \lesssim 0.8$ $M_\odot$ (Tutukov et al., 1982). The change of semimajor axis a in the common envelope stage can be estimated by means of Equation (3). The minimal a of progenitor systems is determined by the necessity to avoid the merging of the components inside the common envelope. The maximal value of a may be found by Equations (4) and (6) upon the condition of drawing components into a semidetached state in the cosmological time by means of a MSW ($M_1 \gtrsim 2.3$ $M_\odot$) or GWR ($M_1 \lesssim 2.3$ $M_\odot$). The systems with He-dwarf primaries evolve under GWR only because they have $M_{He} \lesssim 0.3$ $M_\odot$ and correspondingly completely convective secondaries with $M_2 \lesssim 0.2$ $M_\odot$ for which MSW probably does not exist. The evolution of those extremely low-mass systems has not been studied yet. The frequency of their formation according to Equation (1) and Figure 2 is rather high: ~ 0.005 yr^{-1}. Their lifetimes are of the order of the cosmological time. The discovery of systems with low-mass primaries is hampered by their optical weakness (Ritter and Burkert, 1985). Therefore it is unclear if they are even presented among known cataclysmic binaries, e.g. in catalogues of Patterson (1984) and Ritter (1985). It is worthwhile to mention that systems of this kind may be formed with initial orbital periods a little shorter than ~ 80^m.

The other type of cataclysmic variables results from the evolution of binaries with $M_1 \lesssim 8$–10 $M_\odot$. They consist of degenerate CO- or possibly ONe- (for $M_1 \approx 8$–10 $M_\odot$) dwarfs with masses 0.4-1.4 Mθ and main-sequence stars. These systems are evolving first under the influence of a MSW, and then under a GWR. The frequency of their formation is also close to ~0.005 yr^{-1}. Almost all observed cataclysmic systems belong to this type.

Precataclysmic systems remain detached for several 10^9 yr. They are stationary which hampers their discovery. But about 25 such systems some of which are nuclei of planetary nebulae are known (Bond, 1985).

Using the same formalism we could also find initial positions of other types of binaries that may possibly be related to 'classical' cataclysmic variables: helium stars in a pair with CO or ONe degenerate dwarfs, semidetached twin degenerates, degenerate stars surrounded by heavy disks (Figure 1). To avoid the overpopulation of Figure 2 we omit them. The frequencies of their formation are quite high, but observational counterparts are probably still unknown.

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Now we shall discuss a scenario for the formation of low-mass X-ray binaries. One of the most attractive possibilities is to extend the scenario for cataclysmic binaries to somewhat more massive initial systems with masses of primaries above $\sim 10\ M_\odot$. The primary would produce a neutron star with mass M_{ns} and the low-mass component would fill the Roche lobe due to magnetic braking. The system will not be disrupted by a supernova explosion if $M_{R1} - M_2 < 2M_{ns}$, where M_{R1} is the mass of the primary prior to the explosion. Since the mass of the helium remnant M_{R1} of a $\sim 10\ M_\odot$ star is about $2.5\ M_\odot$ and $M_{ns} \approx 1.4\ M_\odot$ this condition is usually satisfied. Now we can easily estimate with Equation (2) the frequency of the formation of such X-ray binaries taking into account, that systems with $a_f/R_\odot > 10\ M_2/M_\odot$ will be too wide for merging, but those with $a_f/R_\odot < 2.5\ M_2/M_\odot$ will be in overcontact after the common envelope stage. This frequency is equal to $\sim 0.002 \int_0^{0.15} f(90)\,dq_o$.

Numerical results show (see Section 4) that the mass exchange time in such systems is shorter than the cosmological time scale Therefore $\sim 2\times10^{53}$ ergs will be radiated in X-rays by each system. Now we can estimate the current X-ray luminosity of our Galaxy produced by such systems $L \approx 3.4 \times 10^9 \cdot \int_0^{0.15} \Delta q_0 f(q_0) L_\odot$. The observed X-ray luminosity does not exceed $\sim 10^5 L_\odot$, therefore $_o\int^{0.15} f(q_o)\,dq_o$ has to be lower than $\sim 10^{-4}$. But to get the proper number of cataclysmic binaries it is necessary to assume that $\int_0^{0.2} f(q_o)\ dq_o \approx 0.1$. It is unclear now how to resolve this contradiction. Can $f(q_o)$ be so different for stars with $M_1 \approx 3\ M_\odot$ and $M_1 \approx 10\ M_\odot$?

The second attractive possibility to form low-mass X-ray binaries is the transformation of a cataclysmic binary with the accreting ONe-dwarf into the X-ray binary after a supernova explosion. The rate of formation of cataclysmic binaries with ONe dwarfs is $\sim 5\times10^{-5}\ yr^{-1}$ if we assume that only primaries with masses 8-10 $M_\odot$ can form ONe-dwarfs. This frequency as well as the frequency of formation of all cataclysmic variables exceeds considerably the frequency of the formation of low-mass X-ray binaries which is of the order of $3\times10^{-8}\ yr^{-1}$ (Tutukov and Yungelson, 1985). It is possible that the mass-loss by dwarfs during the thermal shell flashes prevents the growth of a dwarf mass (McDonald, 1984), decreasing the probability of supernova explosion.

The main argument against the two briefly discussed above attractive scenarios is the space distribution of low-mass X-ray binaries. They are concentrated towards the bulge of the Galaxy and are members of several most dense globular clusters. The total mass of globular clusters presents only 10^{-4} of the Galaxy mass, but they contain the significant part of all low-mass X-ray binaries. Therefore we have to find the mechanism that explains the concentration of LMXBs to dense clusters and the bulge. The mechanism appears to be unelastic collisions of single neutron stars with single low-mass main-sequence stars (Fabian et al., 1975). Some LMXBs can be products of exchange collisions of single neutron stars with low-mass close binaries, if the number of the latter is not too low (Hills, 1975).

The evolution of LMXBs after their secondaries fill their Roche lobes does not differ from the evolution of cataclysmic binaries with similar masses of components if one neglects the effects of heating of the donor surface by X-rays. Therefore all numerical results, especially Figure 3, can be used well both for the interpretation of the evolution of cataclysmic binaries and LMXBs. The luminosity of a LMXB can be easily estimated as $L_x/L_\odot \approx 10^{12}\dot{M}$ ($M_\odot$ yr^{-1}).

A black hole may also be a member of LMCB, as a result of an unelastic collision in a dense cluster or of a transformation of a neutron star into a black hole due to the accretion.

4. NUMERICAL RESULTS

We shall now discuss numerical results of evolutionary computations for low-mass close binaries. Main driving forces are the MSW, the GWR and the thermonuclear evolution of secondary components if $M_2>0.8$ $M_\odot$. Our discussion is mainly based on several tens of evolutionary tracks for secondaries that have been computed by Fedorova and Yungelson (1984), Iben and Tutukov (1984a), Tutukov et al. (1985, 1986), Tutukov and Yungelson (1985), which cover a broad spectrum of secondary masses (0.5 - 1.5 $M_\odot$), chemical compositions, and evolutionary stages at the instant of Roche lobe overflow. Some of these tracks are shown in Figure 3.

If the mass of the secondary is lower than ~0.8 $M_\odot$, it can fill the Roche lobe only due to AML. In the course of mass exchange these components remain unevolved main-sequence stars. As the mass decreases, the degree of the departure from the thermal equilibrium increases. When M_2 decreases to about 0.3 $M_\odot$ the mass-loss time scale becomes comparable to the thermal time scale of the secondary. Radii of the Roche lobe filling stars with deep convective envelopes which are out of thermal equilibrium exceed radii of thermal equilibrium main-sequence stars. Therefore when the secondary becomes completely convective and its MSW switches off and the driving force of the evolution reduces to the GWR only, the secondary contracts to equilibrium radius interrupting the mass exchange for several hundreds of millions of years. In the absence of the mass exchange, the system is about one hundred times weaker than before. This feature explains the absence of cataclysmic binaries with orbital periods 2^h-3^h (Spruit and Ritter, 1983; Tutukov, 1983).

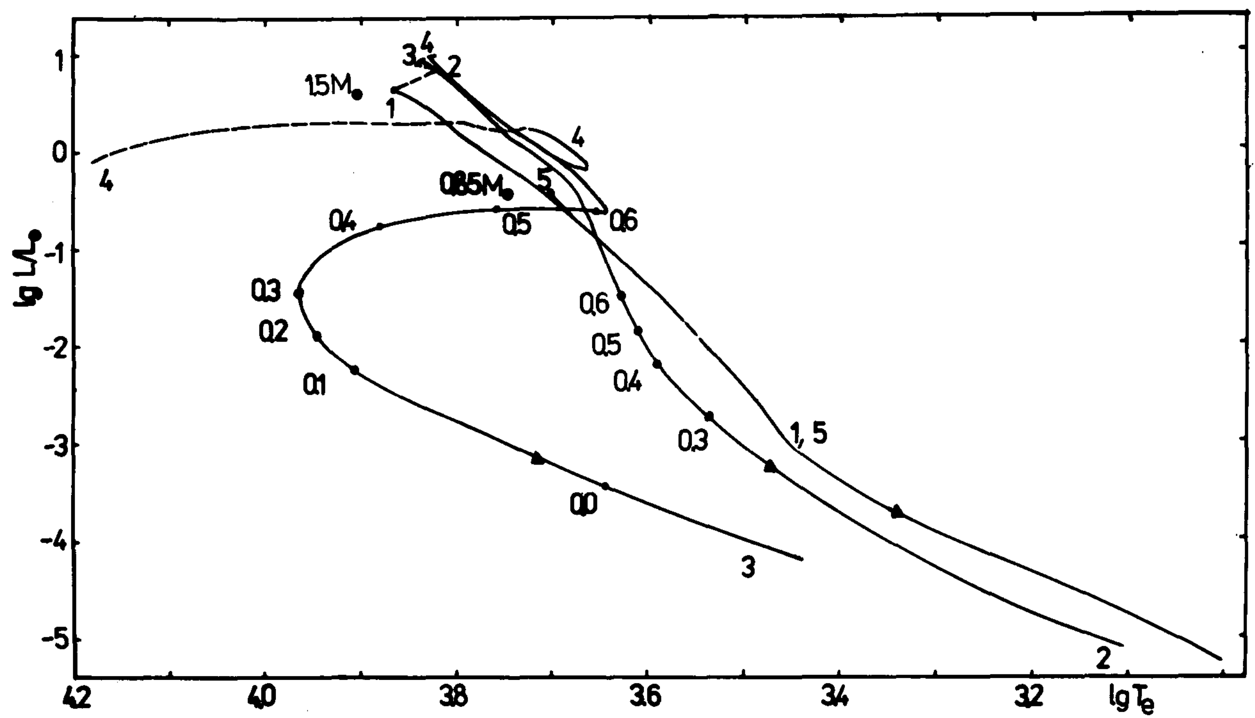

Figure 3. Evolutionary tracks of secondaries in the Hertzsprung-Russell diagram. Continuous lines relate to semidetached stages, dashed lines - to detached ones. Initial masses of components are marked near the tracks. The initial chemical composition is X=0.7, Z=0.03. The parameter of the magnetic stellar wind is α=1. Dots mark the current hydrogen content on the surface of the star. Triangles on tracks 1, 3, 5 mark the instant of the minimal orbital period. The triangle on track 2 marks the instant of the complete mixing. 1 - M_2 = 1.5 $M_\odot$; X_c = 0.7; 2 - M_2 = 1.5 $M_\odot$, $X_c \approx 0.1$; 3 - M = 1.5 $M_\odot$, $X_c = 2 \times 10^{-4}$; 4 - M_2 = 1.5 $M_\odot$, X_c = 0; 5 - M_2 = 0.85 $M_\odot$, X_c = 0.7.

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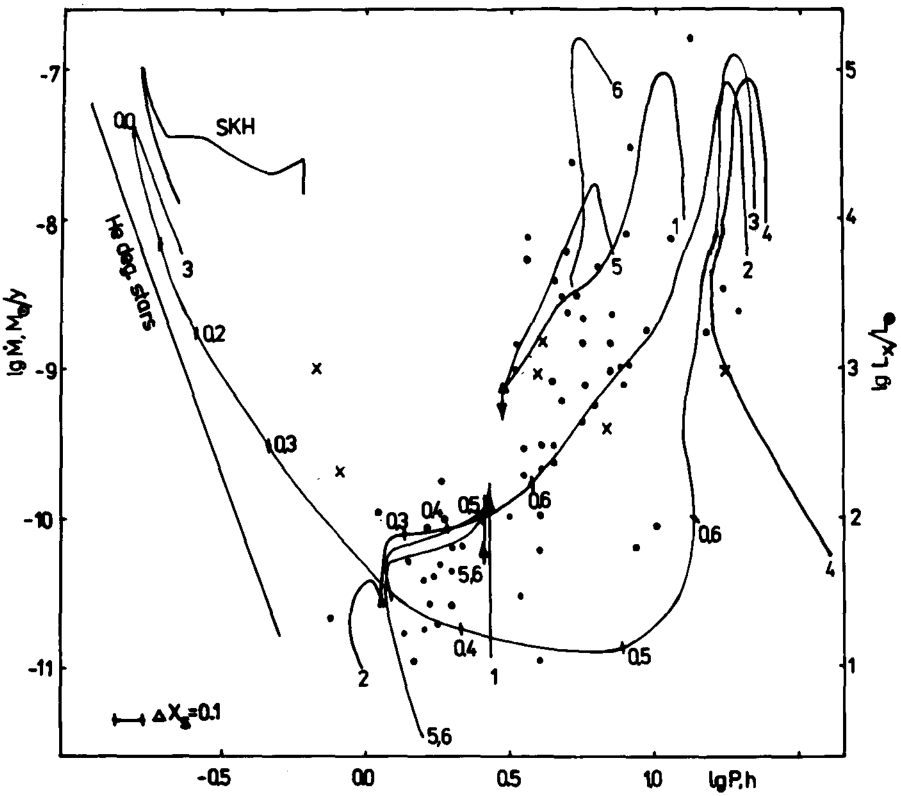

Figure 4. Evolutionary tracks of secondaries in the orbital period-mass exchange rate plane. The right-hand ordinate shows the X-ray luminosity of the accreting neutron star or black hole corresponding to the given M. Tracks 1 to 5 are the same as in Figure 3, track 6 is for M = 0.85 $M_\odot$, X_c = 0.7, α = 0.33 (Tutukov et al., 1986). Track SKH is for a 0.6 $M_\odot$ pure He-star (Savonije et al., 1986). The continuous line in the left shows the track for a He degenerate secondary (Tutukov and Yungelson 1979a). Dots with ticks along the tracks mark the surface hydrogen content. Dots are mass exchange rates of cataclysmic binaries (Patterson, 1984; Tutukov et al., 1986), crosses are mass exchange rates of low-mass X-ray binaries (Tutukov et al., 1985). Triangles mark the instant of complete mixing.

Driven by the GWR closer to the primary, the secondary fills its Roche lobe once more. Now the mass exchange rate is lower than ~10^{-10} $M_\odot$ yr^{-1} and the losing matter secondary remains in the thermal equilibrium until its mass decreases to ~0.1 $M_\odot$. At this time the mass loss time scale again becomes comparable to the thermal time scale and the contraction of the donor slows down. The beginning degeneracy also acts in the same direction. This leads to the alteration of the sign of the orbital period change (Figure 4) at the moment when dln R / dln M becomes equal to 1/3. The orbital period starts to increase (Paczynski, 1981). This quite naturally explains the total absence of dwarf binaries with hydrogen-rich secondaries and with orbital periods shorter than $\sim 80^m$. Mass exchange will continue for several billions of years. The fate of the secondary is not yet conclusively clear. The results of the analysis are still model dependent. Ruderman and Shaham (1983) have found that the secondary will be disrupted in the dynamical timescale when the mass ratio of components becomes ~0.01 which can occur on the cosmological time scale. Hut and Paczynski (1984) obtained lower mass ratios which are not accessible on the cosmological time scale (Tutukov and Yungelson, 1979, Taam and Wade, 1985).

We shall now discuss the evolution of binaries with the secondary mass above $\sim 0.8\ M_\odot$. Their evolution can be divided into three types. If at the Roche lobe overflow the hydrogen content in the core of the secondary is higher than ~0.01 the mass exchange proceeds as in the previous example (see tracks in Figure 3, 4).

The second class is formed by the systems in which the secondary components have at the instant of the Roche lobe overflow a hydrogen content in their centers that is lower than ~0.01 or even very low mass ($M_{He} \sim 0.01\ M_\odot$) helium cores. The mass exchange in this case starts in the thermal time scale of the secondary, but $\dot{M}$ decreases quickly to $\sim 10^{-10}\ M_\odot\ yr^{-1}$ (Figure 4). For some time the orbital period remains almost constant and then begins to decrease. The secondary conserves the radiative core until its mass becomes $\sim 0.02\ M_\odot$, therefore these systems continuously evolve through the $2^h - 3^h$ gap, saving the hope to find in the future cataclysmic binaries with such orbital periods. The remarkable property of these binaries is the possibility to achieve very low (up to several min) orbital periods. As the hydrogen content of the envelope decreases, the radius of the secondary also decreases rapidly, because the radii of the helium stars are very small. However, due to a high efficiency of GWR the system remains semidetached, which lead to a rapid decrease of the orbital period to values as low as $\sim 10^m$. The final state of the system is unclear like in the previous case. It is interesting that the decrease of the orbital period is accompanied by a strong increase of the mass exchange rate (Figure 4). The observed mass exchange rates and short orbital periods of several low-mass X-ray binaries agree rather well with the theoretically predicted values.

It is possible, of course, to assume that these short period systems have pure helium nondegenerate donors. Evolutionary track of such a binary in the plane lg P -lg $\dot{M}$ is shown in Figure 4 according to Savonije et al. (1986). Binaries with pure helium nondegenerate stars as donors have to have much higher mass exchange rates than those observed until now for cataclysmic variables as well as probably for LMXB. Also, as it was noted by Nelson et al. (1986) the

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intrinsic optical luminosity of the heliumburning secondaries would be much higher than is observed for ultra-short period binaries.

The third type of evolution of low-mass close binaries will occur if the secondary at the instant of Roche lobe overflow has a helium degenerate core with a mass above ~0.01 $M_\odot$, but does not yet have a deep convective envelope that prescribes a fast mass loss and the formation of the common envelope (Figures 2, 3). The mass exchange begins in the thermal time scale of the donor, but quickly relaxes to a lower level determined by the MSW and shell nuclear burning time scales (Iben and Tutukov, 1984; Tutukov et al., 1986). The orbital period of the system does almost not change (Figure 4). Some long period cataclysmic binaries (GK Per) and low-mass X-ray binaries (Sco X-1) can belong to this class. The secondary ends as a very low-mass white dwarf ($M \approx 0.13 - 0.25\ M_\odot$, Kraicheva et al., 1986).

Figure 4 compares predicted mass exchange rates with observed ones. The general agreement is quite satisfactory, but it is evident that many systems have too low mass exchange rates. The ultimate reasons for this discrepancy are not yet known, we can as yet only name several possibilities. The precision of observational estimates remains poor, it is not better than to a factor 2-3. It is also possible that some kind of instability of the donor alters the mass exchange rate. For example, observations of solar type dwarfs have shown that their chromospheric activity has a recurrent nature. Their MSW can therefore also be variable, which would immediately result in the variations of the mass exchange rate.

There exists an interesting possibility for the variation of the mass exchange rate if thermal flashes occur in the envelope of an accreting dwarf. A thermal flash leads to the expansion of hydrogen-rich envelope beyond the orbit of the system. The envelope can probably be dispersed only due to a friction of the double core. A simple analysis shows that for $q \gtrsim 0.7a/R_{ce}$ (R_{ce} being the radius of the common envelope) the radius of the Roche lobe will increase as $\Delta R/R \approx -\Delta M/(M_1+M_2)$ where ΔM is the mass of the dispersed common envelope. The rate of the mass exchange is a function of the stellar radius excess over the Roche lobe radius. According to Hut and Paczynski (1984) $\Delta\dot{M}/\dot{M} \approx R/H_p$ where H_p is the pressure scale height in the atmosphere of the star. It is now evident that in order to change M significantly it is necessary to have $\Delta M/M \approx H_p/R \approx 10^{-4}$. It means that the loss of the ~$10^{-4}\ M_\odot$ nova envelope is enough to change the mass exchange rate for $\Delta M/\dot{M} \approx 10^3$-$10^6$ years. In this case the track in Figure 4 will resemble a sinusoidal curve with the upper bound close to an undisturbed mass exchange curve. Is at the instant of the thermal flash in the envelope of an accreting dwarf $q<0.7a/R_{ce}$ the semimajor axis would decrease after the common envelope phase. This would increase the mass exchange rate and the frequency of thermal flashes and may result in the disruption of the completely convective secondary.

Tutukov and Yungelson (1979) pointed out that the brightest short period cataclysmic binaries ($P<2^h$) are almost three magnitudes weaker than the brightest long period cataclysmic variables ($P>3^h$).

We assume here that most radiation arises in the hot spot on the edge of the accretion disk. In this case the number of homogeneously distributed stars in space that are brighter than some certain magnitude is $n \propto M^{3/2} \cdot P \cdot \dot{P}^{-1}$. Values of n for two evolutionary tracks are shown in Figure 5. Since $d\lg n/dm_v=0.6$, it is possible by a corresponding choice of scales for n and m_v to compare directly the theoretical distribution of the magnitudes of brightest stars over the orbital period for any evolutionary track with the observed one (Figure 5). Figure 5 explains a higher brightness of long-period cataclysmic systems and ultra-short ($p<1^h$) binaries mainly by their relatively high mass exchange rates.

5. CONCLUSION

We have briefly discussed main properties of evolution of low-mass binaries with compact components whose evolution is accompanied by flashes of different types. The main driving forces of their evolution are the angular momentum loss by GWR, and nuclear evolution of the secondary if its initial mass exceeds $\sim 0.8\ M_\odot$. If the cosmological time scale a mass of the secondary will become $\sim 0.01\ M_\odot$ if it is a hydrogen-rich star (Tutukov and Yungelson, 1979; Taam and Wade, 1985).

The assumption about the switch-off of a MSW at the instant when the secondary becomes completely convective allows to explain the 2^h-3^h gap in the distribution of cataclysmic binaries over orbital periods. But the reasons for this switch-off remain unknown. It is unclear if it is related to the exhaustion of the relic magnetic field (Tutukov, 1983) or to the change of the boundary conditions for dinamo-mechanism (Spruit and Ritter, 1983) or to something else.

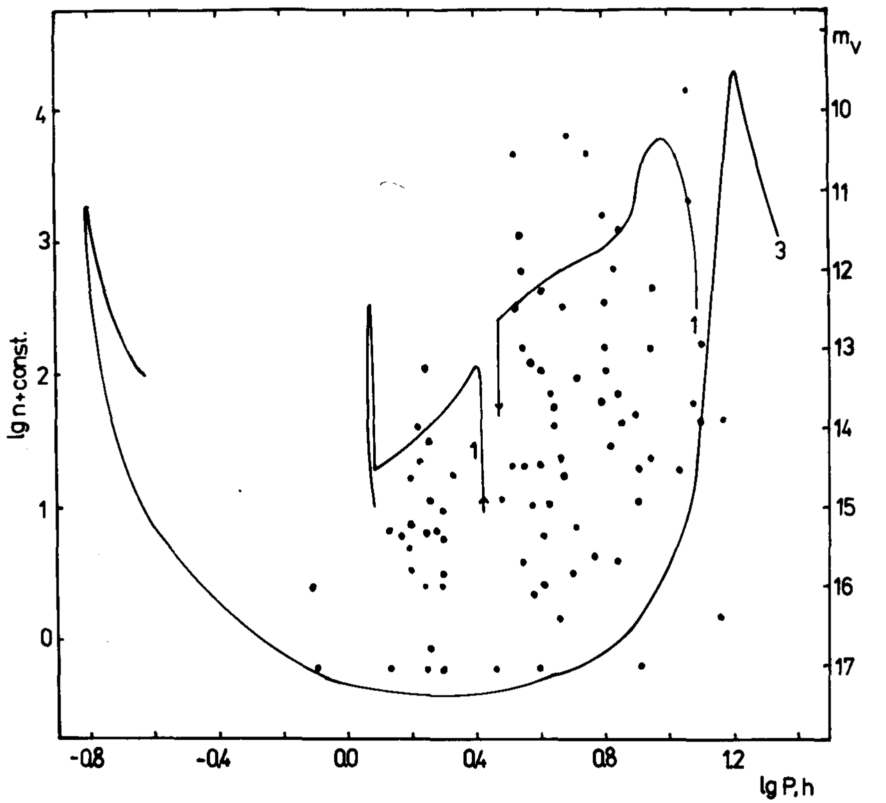

Figure 5. Dependence of the relative number of cataclysmic variables per unit interval of logarithm on the period (left-hand ordinate) and dependence of the visual magnitude on period (right-hand ordinate). Numbers of tracks are the same as in Figure 3. Values of m_V are from Ritter (1984). Details are given in the text.

It is not yet clear either what are the limits of the semi-empirical formalism based on the Skumanich law of the rotation braking for low-mass main-sequence stars. There is also no answer to one more very important question: is the MSW a property only of secondaries with convective envelopes and radiative cores or is it also inherent to secondaries with radiative envelopes?

A change of the value of the parameter α in Equation (5) allows to investigate the influence of the variation of MSW strength on numerical results (Tutukov et al., 1986). The computations have shown that even only a threefold decrease of α changes the track of the system in the M - P plane significantly, increasing the width of the gap in the orbital periods space (Figure 4). The study of algols with $\alpha=1$ explains satisfactorily their parameters. The fact that α is the same for a rather wide ensemble of stars with magnetic braking of rotation can be explained only by future theories of the MSW.

Two main problems, which are very important for the study of the origin and evolution of cataclysmic binaries, remain unsolved. They are the distribution of binaries over initial mass ratios and the physics of common envelopes. We have to understand what the relative number of binaries with $q \approx 0.1 - 0.2$ is. How to get the necessary number of binaries and to avoid the overproduction of low-mass X-ray binaries?

One standard problem for binaries is the problem of mass and angular momentum loss from systems. All numerical computations have been performed under the assumption that the total mass of the systems is conserved. But thermal flashes in the envelope of the accreting dwarf and a successive formation of short-living common envelopes evidently lead to an efficient mass loss from the system. This mass loss decreases an average mass exchange rate in the system as compared to the conservative case. In LMXBs another mode of the mass loss from the system is possible. It is the stellar wind induced by the irradiation of the low-mass donor. This interesting case has not been studied in detail so far.

Hertz and Grindlay (1983) discovered that the luminosity function for the brightest globular cluster X-ray sources is bimodal with a gap from ~10 to ~250$L_\odot$. A similar gap exists also for galactic plane sources (Hertz and Wood, 1985). Some bright X-ray sources are placed in Figure 4. Hertz and Wood (1985) assume that weak sources are cataclysmic variables and bright sources contain neutron stars as accretors. Theoretical tracks 1, 5, 6 predict a gap in L_x from ~100 to ~1000 $L_\odot$, which evidently does not coincide with the observed one.

Most important is that both theory and observations of cataclysmic variables surely predict the existence of a considerable number of LMXBs with neutron stars driven by GWR, with $L_x \approx 10{-}100$ $L_\odot$, just inside the observed gap. If we assume, like Hertz and Wood (1985) that the efficiency of transformation of gravitational energy into X-rays is 1, then sources with periods $1^h{-}2^h$ and $\dot{M} \approx 2\mathrm{x}10^{-11}{-}10^{-10}$ $M_\odot$/yr would determine the lower bound of the distribution for bright sources. But two questions immediately arise here. Where are numerous systems with $\dot{M}<2\mathrm{x}10^{-11}$ $M_\odot$/yr? Why does no known bright LMXBs have a period between 1 and 2^h? This important problem appears to be unsolved to us.

An important problem is posed by a period distribution of cataclysmic variables and LMXBs. Why do only about one percent of the cataclysmic variables have periods shorter than 1^h, while 2 out of 6 LMXB with known orbital periods have $P<1^h$?

REFERENCES

Bath, G.T., 1975, Mon. Not. R. Astron. Soc., 171, 311.

Bond, H.E., 1985, in Cataclysmic Variables and Low-Mass X-Ray Binaries, ed. D.Q. Lamb and J. Patterson (Reidel, Dordrecht), p. 15.

Cannizzo, J.K., Wheeler, J.C. and Ghosh P., 1985, in Cataclysmic Variables and Low-Mass X-Ray Binaries, ed. D.Q. Lamb and J. Patterson (Reidel, Dordrecht), p. 307.
Edwards, D.A., 1985, Mon. Not. R. Astron. Soc., 212, 623.
Fabian, A.C., Pringle, F.E. and Rees, M.J., 1975, Mon. Not. R. Astron. Soc., 172, 15.
Fedorova, A.V. and Yungelson, L.R., 1984, Space Sci., 103, 125.
Gurevich, A.L. and Lebedinskij, M.A., 1947, Zh. Eksper. i Teor. Fiz., 17, 792 (in Russian).
Hertz, P. and Grindlay, J.E., 1983, Ap. J., 275, 105.
Hertz, P. and Wood, K.S., 1985, Ap. J., 290, 171.
Hills, T.G., 1975, Astron. J., 80, 809.
Hut, P., Paczynski, B., 1984, Ap. J., 284, 675.
Iben, I., Jr. and Tutukov, A.V., 1984a, Ap. J., 284, 719.
Iben, I., Jr. and Tutukov, A.V., 1984b, in High Energy Transients in Astrophysics, ed. S.E. Woosley (Amer. Inst. Phys., New-York).
Iben, I., Jr. and Tutukov, A.V., 1985, Ap. J. Suppl., 58, 611.
Kraft, P.P., Mathews, J. and Greenstein, J.L., 1962, Ap. J., 136, 312.
Kraicheva, Z.T., Tutukov, A.V. and Yungelson, L.R., 1986, Astrofizika, in press.
MacDonald, T., 1984, Ap. J., 283, 241.
Maraschi, L. and Cavaliere, A., in Highlights of Astronomy, 4, ed. E.A. Müller, p. 127.
Meyer, F. and Meyer-Hoffmeister, E., 1979, Astron.Ap. 78, 167.
Osaki, Y., 1974, Publ.Astron.Soc.Japan, 26, 429.
Paczynski, B., 1976, Structure and Evolution of Close Binary Systems, ed. P. Eggleton (Reidel, Dordrecht), p. 75.
Paczynski, B., 1981, Acta Astron., 21, 4.
Paczynski, B., 1985, in Cataclysmic Variables and Low-Mass X-Ray Binaries, Eds. D.Q. Lamb, J. Patterson (Reidel, Dordrecht, p.1).
Patterson, J., 1984, Ap. J. Suppl., 54, 443.
Popova, E.I., Tutukov, A.V. and Yungelson, L.R., 1982, Ap. Space Sci, 88, 155.
Rappaport, S., Verbunt, F. and Joss, P.C., 1983, Ap. J., 275, 713.
Ritter, H., 1984, Preprint MPA-106.
Ritter, H. and Bunkert, A., 1985, in Recent Results on Cataclysmic Variables, Bamberg, p. 17.
Ruderman, M.A. and Shaham, T., 1983, Nature 304, 425.
Savonije, G.I., de Kool, M. and Van den Heuvel, E.P.J., 1986, Astron. Ap., 155, 51.
Skumanich, A., 1972, Ap. J., 171, 561.
Spruit, H.C. and Ritter, H., 1983, Astron. Ap., 124, 267.
Taam, R.E. and Wade, R.A., 1985, Ap. J., 293, 504.
Tutukov, A.V., Yungelson, L.R. and Klayman, Ya., 1973, Nauchn. Inform., 27, 3.
Tutukov, A.V. and Yungelson, L.R., 1979a, Acta Astron., 29, 665.

Tutukov, A.V. and Yungelson, L.R., 1979b, in Mass Loss and Evolution of O-type stars, Eds. P.S. Conti and de Loore, Reidel, Dordrecht, p. 216.

Tutukov, A.V. and Yungelson, L.R., 1981, Nauchn. Inform., 49, 3.

Tutukov, A.V. and Yungelson, L.R., 1985, in Recent Results on Cataclysmic Variables, Bamberg, p. 7.

Tutukov, A.V. and Yungelson, L.R., 1985, Nauchn. Inform. (in press).

Tutukov, A.V., Fedorova, A.V., Yungelson, L.R., 1982, Pis'ma Astron. Zh., 8, 365.

Tutukov, A.V., Fedorova, A.V., Ergma E.V. and Yungelson, L.R., 1985, Pis'ma Astron. Zh., 11, 23.

Tutukov, A.V., Fedorova, A.V., Ergma, E.V. and Yungelson, L.R., 1986a, Astrofizika, 24, 85.

Tutukov, A.V., Fedorova, A.V. and Yungelson, L.R., 1986b, Nauchn. Inform. (in press).

Tutukov, A.V., 1981, in Fundamental Problems in Stellar Evolution, eds. D. Sugimoto, D.Q. Lamb, D.N. Schramm (Reidel, Dordrecht), p. 116.

Tutukov, A.V., 1983, Preprint of Illinois Univ., IAP 83-25.

Verbunt, F., 1981, Mon. Not. R. Astron. Soc., 209, 227.

Verbunt, F. and Zwaan, C., 1981, Astron. Ap., 100, L7.

Webbink, R.F., 1985, preprint.

Whelan, J.A.J. and Iben, I. Jr., 1983, Ap. J., 186, 1007.

Yungelson, L.R. and Massevitch, A.G., 1983, Soviet Sci. Revs., Astrophys. and Space Phys. Revs., ed. R. Syunyaev, 2, p. 29.

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