EVOLUTION OF CLOSE BINARIES

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1. INTRODUCTION AND SUMMARY

Most stars of our Galaxy's disk are double. The existing estimation of duplicity α_d range from $\sim$ 50-70 % (Abt, Levy, 1976, Abt, 1979) to $\sim$ 100 % (Kraitcheva et al., 1978). About half of all stars are close binaries (CB) and hence their components fill their Roche lobes during evolution. This accounts for the constantly increasing interest to their evolution. Several review papers were published in the last years: Paczynski (1971), Tutukov et al. (1975), van den Heuvel (1976), Massevitch et al. (1976), Thomas (1977), Paczynski (1979), Webbink (1979b), Yungelson and Massevitch (1980). The subject matter of close binary evolution is very wide now, therefore, I will limit myself to the review of modern scenarios for evolution of massive ($M \gtrsim 10\ M_\odot$) close binaries (MCBS) and close binaries of moderate ($M \lesssim 10\ M_\odot$) mass.

CB formation is a part of the fragmentation process determined mainly by rotation. Our catalog of spectroscopic binaries has now data on $\sim$1050 binaries and makes it possible, taking into account numerous selection effects, to find "innate" distributions of close binaries over mass of primaries M, ratio of mass q and large semiaxis (Tutukov, Yungelson, 1979). These distributions can be represented as $dN \approx 0.5(M/M_\odot)^{-2.3}\ d(M/M_\odot)$ per yr, $q \approx 1$, $d\alpha_d \approx 0.17\ d \ln \alpha$ for stars with $1 \lesssim M/M_\odot \lesssim 40$. The remarkable absence of unevolved binaries with $M \gtrsim 1.5\ M_\odot$ and $\alpha \lesssim 10\ R_\odot$ and the low number of binaries with $\alpha \lesssim 10\ R_\odot$ in general give a good possibility to advance the theory of binary formation and early stages of evolution of binaries with $M \lesssim 10\ M_\odot$ (Tutukov, Yungelson, 1979).

Most evolutionary computations for close binaries were

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performed under "conservative" assumptions M_t = const and $J = (Ga/M_t)^{1/2} M_1 M_2$ = const, i.e. the binary mass M_t and the orbital angular momentum J are constant during evolution. The real evolution is nonconservative of course. Examples of radiopulsar PSR 1913+16 in the close binary, cataclysmic variables and other stars show that close binaries can lose most part of its mass and the orbital momentum. The mass and momentum loss is also important for nonexplosive stages of evolution. The formalism and some analytical estimations on influence of mass and momentum loss on evolution were proposed by Tutukov and Yungelson (1971). Evolution of massive stars under mass loss was investigated also by Vanbeveren et al. (1979). It seems now that in most cases the "nonconservative" evolution does not change the qualitative picture - scenarios which were developed on "conservative" evolution computations mainly.

2. SCENARIO AS A MEANS OF THE THEORY OF STELLAR EVOLUTION

Observations of stars give information only about outer, optically thin part of stars. But all main processes of energy generation and transfer occur deeply inside stars. That leads to great difficulties in the purely theoretical approach to the stellar evolution consisting in the search of main determining physical causes based on observational data on their sometimes rather distant consequences. This property of stellar evolution theory makes difficult the fast and effective selection of models and frequently decreases prognostic value of these models. All that and complexity of the physical processes involved in stellar evolution practically exclude the axiomatic approach to the theory which is the most attractive from the logical point of view.

The scenario approach is one of effective means to overcome at least partly this obstacle. A scenario is a logically self-consistent picture of the main stages in development of a star and reason-consequence relation between them based on the whole accessible observational and theoretical information on the process under consideration. Modern scenarios are based from theoretical point of view on numerous evolutionary computations made in the last decades and from observational point of view on observations in optical, UV, IR, and X-ray ranges of electromagnetic spectra. The attractive property of the scenario approach consists in the possibility of an operative and flexible reaction to new observational and theoretical information with the aim to have a fullest picture consistent with all fundamental observational and theoretical data.

3. EVOLUTION OF MASSIVE CLOSE BINARIES ($M_1 \gtrsim M_2 \gtrsim 10\ M_\odot$)

We will call MCBS double stars both components of which have masses above M_{SN}, where M_{SN} is the minimal mass of nonaccreting component of a binary exploding as a supernova. This value was estimated as $M_{SN} \approx 10^{+3}_{-2}\ M_\odot$ (Massevitch, Tutukov, 1980). The first variant of the scenario was proposed by van den Heuvel, Heise (1972) (to 1.5 stage) and Tutukov, Yungelson (1973) (through 1.6-1.9 to 1.11 stage) independently. This scenario unites into a single evolutionary sequence many objects related to evolution of MCBS of B and C types (see Fig. 1). Lifetimes and numbers of galactic MCBS in appropriate evolutionary stages are also approximately pointed there. This variant of scenario describes the behavior of B and C-types of MCBS which form about 90 % of all MCBS (Kraitcheva et al., 1978). Most part of the lifetime of such MCBS is spent in 1.1 stage. The usual space velocities of such stars are ~ 10 km/s and typical distances from the Galactic plane are ~ 80 pc. It is possible that most massive components with $M \gtrsim 30\ M_\odot$ can lose the noticeable part of their mass by stellar wind before the primary fills its Roche lobe.

Evolution of B-systems after filling the Roche lobe strongly depends on the input criteria of convective stability in the zone of variable molecular weight (Tutukov et al. 1975). If the gradient of molecular weight ∇_μ is taken into account (Ledoux criterion, L-models), then exchange occurs on Kelvin-Helmholtz time scale: $T_{KH} \approx 3 \cdot 10^7 (M/M_\odot)^2 (R_\odot/R)(L_\odot/L)$years. The usual hydrogen abundance on the surface of remnant is ~ 0.2. If ∇_μ is not taken into account (Schwarzschild criterion, S-models), then the exchange time scale depends on initial mass (Tutukov et al., 1975). For stars with $M \lesssim 20\ M_\odot$ the exchange time scale is of the order of T_{KH} but for more massive stars this time scale is close to the core helium burning time which is about ten % of the main sequence time scale.

The product of exchange for L-models is a helium star with $M_{He} \approx 0.1 (M\ /M_\odot)^{1.4} M_\odot$ and $T_e \approx 10^5$ K. The effective temperature of the remnant of S-models with initial mass $M/M_\odot \gtrsim 13\ M_\odot$ is rather low $T_e \lesssim 3 \cdot 10^4$ K (Chiosi, Summa, 1970, Tutukov et al., 1975). But Kraitcheva (1974) found that mass loss with the observed rate $\sim 3 \cdot 10^{-6} M_\odot$/yrs leads to increasing the temperature of the remnant up to $\sim 10^5$K. Thus in both cases we can get high temperature and luminosity remnants resembling effective temperatures of WR stars. Mass loss explains existence of two types of WR stars - WN and WC stars - as a result of successive uncovering deep layers of stars affected by hydrogen and

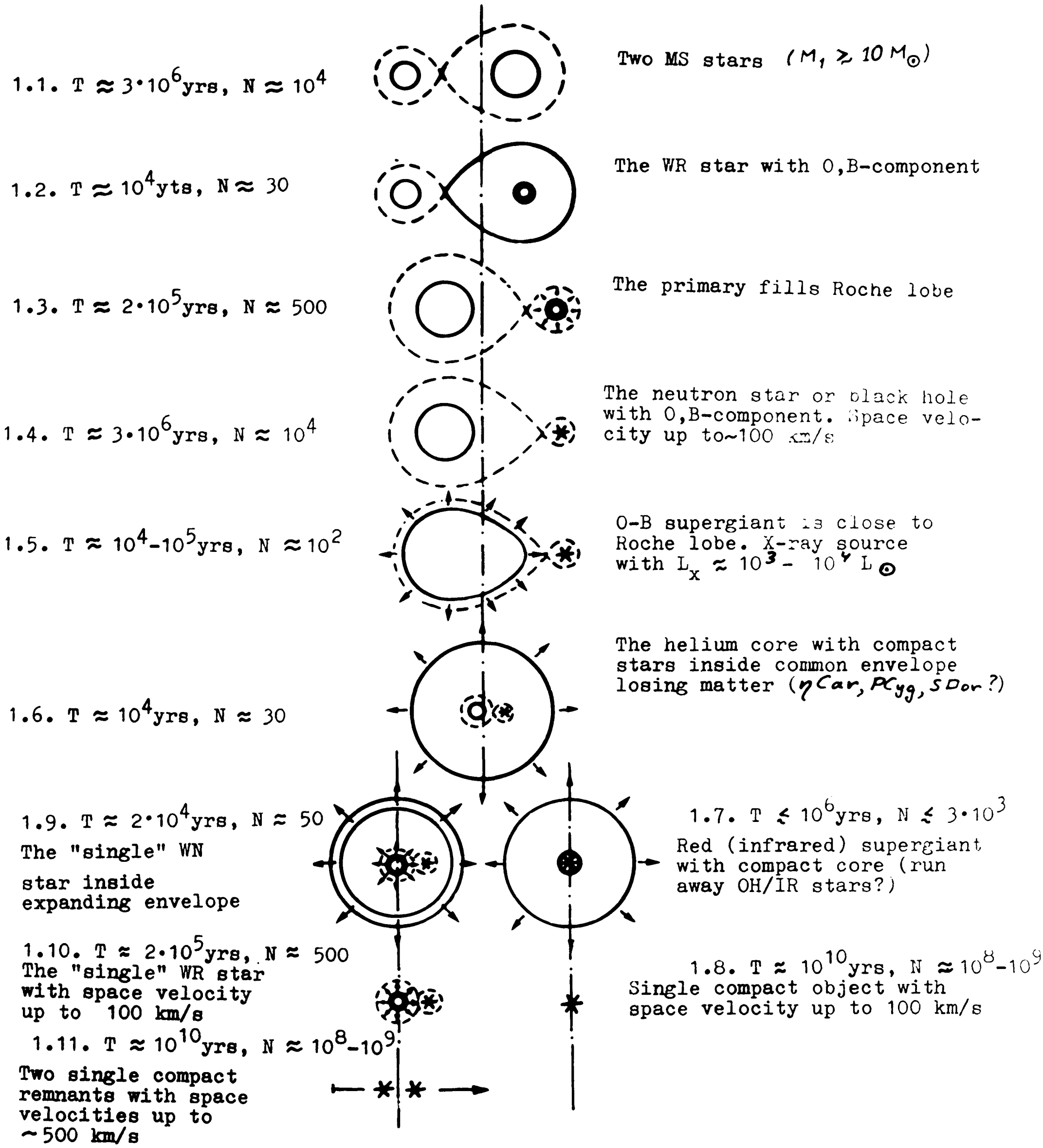

Fig. 1. Evolutionary scenario for massive close binaries .

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helium burning (Tutukov, Yungelson, 1973). The comparison of relative numbers of observed WN and WC stars of the same absolute magnitude leads to the conclusion that the ratio of numbers of WR in WN stage and WC stage increases with luminosity (the initial mass) of the star. For WR stars from Moffat and Isserschtedt (1979) catalog $N_{WN}/N_{WC} \approx 3 \pm 0.7$ for $M_v \lesssim -6^m$ and only $\sim 0.8 \pm 0.1$ for $M_v > -6$. But to transform this ratio into the ratio of life times one needs reliable scales of bolometric corrections for WN and WC stars which are absent as yet. The relatively small number of WR stars and strong selection effects hinder determination of the low mass border of pre-WR stars. The present-day estimation of this value is $\sim 15\ M_\odot \pm 5\ M_\odot$. It is possible that WR stars can form in binaries only (Vanbeveren, Conti, 1979).

Cooling of the nucleus of a massive star by UFI neutrino shortens carbon, neon, silicon burning times to several thousand years only and after that exprimary explodes as a supernova leaving a neutron star with the mass $\sim 1.4\ M_\odot$. The system loses part of the matter but is conserved as a double obtaining the space velocity up to ~ 100 km/s, which is a typical velocity of "run away" OB-stars. Such a velocity is quite enough to reach during the optical component lifetime z-distance $\sim 10^3$pc. The duplicity of such a star with a neutron star or black hole as a component is hardly discoverable due to high mass ratios. HD59543 (Gott, 1972), HD108 (Hutchings, 1975) are examples of such systems. Wide triple systems will be disrupted after the loss of the run away binary. The number of run away stars is comparable with the number of usual O,B-stars (Stone, 1979). It is remarkable that almost all stars with $M \gtrsim 50\ M_\odot$ are fast (Stone, 1979) and placed mainly near MS in the HR diagram (Humphreys, Davidson, 1979). It is possible that the presence of a close relativistic component prevents them from long blue and red supergiant stages (Tutukov, Yungelson, 1980b).

The stellar wind matter is swallowed up partly by the relativistic component which leads to the X-ray emission (Davidson, Ostriker, 1973, Tutukov, Yungelson, 1973b). Of such nature are X-ray sources in massive binaries like Cen X-3. The X-ray luminosity remains rather weak until the optical component approaches the Roche lobe. But the Roche lobe filling itself leads to switching out of the X-ray radiation due to high opacity. This determines the time scale of the X-ray stage (Ziolkowski, 1977). Numerical computations of MCBS evolution with the observed mass loss rate allow us to estimate the number of massive X-ray binaries with X-ray luminosity above $10^3\ L_\odot$. This number was found to be $\sim 10^2$ if the optical component is a MS

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star and ~ 10 if it is a supergiant (Massevitch et al., 1979). The X-ray stage is the longest one ($\sim 3 \cdot 10^5$ yrs) for binaries with the optical component mass $\sim 20\ M_\odot$. These estimations agree with observations. Accretion of the disk matter accelerates rotation of a neutron star in the time scale $T_\omega \approx 10^{4.5}/p/(L_x/10^{37})$ (yrs), which agrees with the observed acceleration of X-ray pulsars (Mason, 1979).

The filling of the Roche lobe by the optical component leads to the common envelope formation as the accretion rate for compact component does not exceed $\sim 10^{-8} M_\odot$/yr. The point L_2 has no dynamical significance, of course, in the absence of solid body rotation. The unique object SS433 may be a system just before the common envelope formation (van den Heuvel et al., 1980). The common envelope stage of MCBS was proposed by Paczynski (1974) and studied numerically by Taam et al. (1978), Tutukov and Yungelson (1979). The estimated number of common envelope stars in Galaxy is ~ 50. They may have high mass loss rate and luminosity. It is possible that η Car, P Cyg, S Dor and other stars of this type are common envelope binaries (Tutukov, Yungelson, 1979).

If the orbital period of MCBS just before the Roche lobe filling does not exceed $\sim 20^d$, then a supergiant with a neutron core (Thorne-Zytkow object) forms. If the orbital period of MCBS exceeds $\sim 20^d$, then after the thermal time of the optical star envelope ($\sim 10^4$ yrs) the close binary consisting of WR star and the neutron star forms inside the lost envelope. Remnants of that envelope can be observed $\sim 2 \cdot 10^4$ yrs as a bright nebula with the radius of ~ 1 pc around a "single" WN star (Massevitch et al., 1976). Several percent of all WR stars should have observed nebulae nearby. Nine of such "single" WN stars were found in our Galaxy and their properties agree well with theoretical predictions (Massevitch et al., 1976; Lozinskaya and Tutukov, 1980). One of them HD50896 (EZCMa) was proposed to be a single line binary with the mass of unseen component $\sim 1.4\ M_\odot$ (Moffat, Seggewiss, 1979) and z-coordinate ~ 280 pc (Moffat, Isserstedt, 1979). It is worth to add that accretion of the common envelope matter is negligible in comparison with mass loss. Otherwise heavy black hole formation would be inevitable which would exclude the system disruption during the second supernova explosion and formation of many pulsars in close binaries.

The absence of ring nebulae around WR+O,B systems indicates the absence of intense mass loss from the systems in 1.2 stage. So, the dissipation of the expanding nebula leaves a"single" WR star (1.10) with the unseen relativistic component as it was proposed by us (Tutukov, Yungelson,

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1973a). But these stars conserve high space velocities and z-coordinates. Moffat and Isserstedt (1979) found that the $\langle z \rangle \approx 80$ pc (25 stars) for WR+O,B stars and $\langle z \rangle \approx 130$ pc (31 stars) for "single" WR stars. These results agree well with our predictions.

Exhaustion of nuclear fuel in the core of WR leads to a supernova explosion. If the presupernova mass is α M which is close to the helium remnant mass, and the mass of the relativistic remnant is β M , and initial masses of components are equal to M , then the condition of disruption of the conservative binary is $\alpha(2-\alpha)-\beta > 2\beta(2-\alpha)$. From the results by Weaver and Woosley (1980) $\beta \approx 1.4 M_\odot/M$. Now the condition of disruption for $M_{SN} = 10\ M_\odot$ is $\alpha \gtrsim 0.37$. Our computations give $\alpha \approx 0.1\ (M/M_\odot)^{0.4}$ which is not enough for disruption of such systems. To disrupt all MCBS the mass of helium remnant αM or M_{SN} should be increased ($M_{SN} \lesssim 13\ M_\odot$). Some systems can survive as binaries like the pulsar in the close binary. As the semiaxes of MCBS decrease in the common envelope stage, young neutron stars (future pulsars) can get space velocities up to 500 km/s after disruption (Tutukov, Yungelson, 1979a).

Let us discuss disruption of wide massive binaries the components of which do not fill Roche lobes (P $\gtrsim$ 3 yrs). Condition of disruption of such systems in apoastres of their orbits is: $(1-e)\ M_1 - (1+e)\ M_2 \gtrsim 2\ M_{1R}$, where M_1 and M_2 are masses of components before explosion and M_{1R} is the mass of remnant. The eccentricity of orbit e may be innate or due to the first supernova explosion. Now the condition of disruption of all systems is $e < (\alpha/\beta\ -3)\ /\ (\alpha/\beta\ +1)$, where αM is presupernova mass. The numerical analysis shows that several percent of wide systems can conserve as binaries with orbital period exceeding 5-10 yrs also after the second explosion. The pulsar in long period binary discovered by Manchester et al. (1980) could not form in such a way if the eccentricity of this system is really close to zero.

The lifetime of the Thorne-Zytkow object is limited to $\sim 10^6$ yrs probably mainly due to mass loss. Otherwise the number and total luminosity of (infra)red supergiants would be too high. Fast mass loss ($\dot{M} \gtrsim 10^{-5}\ M_\odot$/yrs) transforms such stars into infrared sources with high space velocities. Some of OH/IR stars have space velocities up to $\sim$ 70 km/s according to Habing (1977) but their nature is not clear as yet.

In all cases single neutron stars (black holes) of high (as a rule) space velocities will form at the end of MCBS evolution. We supposed that radio pulsars consist of two kinematically different populations in our Galaxy (Tutukov, Yungelson, 1973). One of them consists of "slow" pulsars ($\langle z \rangle = 80$ pc) which are products of wide binaries and the other ($\langle z \rangle \approx 150$ pc) consists of "fast" pulsars which are products of MCBS. Predicted high space velocities agree well with the observed velocities (Hanson, 1979, Helfand, Tademaru, 1977).

The significant number of neutron stars may form in conservative evolution case in CB with $5.5 \lesssim M/M_\odot \lesssim 10$. The primary forms a degenerate dwarf with mass M_α. The secondary having accreted most part of the primary envelope becomes more massive than the minimal mass of supernova M_{SN} and at the end explodes as SN. Simple considerations show that the system will be destroyed at that moment if $M_\alpha/(\alpha-2\beta) < M_{SN}$. This condition does not depend either on the initial mass ratio or mass loss which determines only the total number of such systems. If $\beta \approx 1.4\, M_\odot/M$ (Weaver, Woosley, 1980), the disruption condition for $M_\alpha = 1.2\, M_\odot$ transforms into $\alpha \gtrsim 0.4$ (if $M_{SN} = 10\, M_\odot$) or $M_{SN} \gtrsim 14\, M_\odot$ (if $\alpha \approx 0.1\, (M/M_\odot)^{0.4}$). So, if $\beta \approx 1.4\, M_\odot/M$, then to disrupt most of such binaries one needs to assume that $M_{SN} \gtrsim 14\, M_\odot$ or that real α exceeds the theoretical estimation of the value. The violation of the disruption condition leads to the neutron star formation in the close eccentric binary like PSR 1913+16.

4. EVOLUTIONARY SCENARIO FOR CLOSE BINARIES OF MODERATE MASS ($1 \lesssim M\ /M_\odot \lesssim 10$)

Borders of the mass range are determined by condition of degenerate dwarf formation in the end of evolution of components. This scenario remains rather poorly developed and Fig. 2 is only a preliminary sketch.

The analyses of distribution of spectroscopic binaries of different mass over semiaxes a have shown the absence of unevolved binaries with $M \gtrsim 1.5\, M_\odot$ and $a \lesssim 10\, R_\odot$ (Svechnikov, 1969, Kraitcheva et al., 1978). Kraitcheva et al. (1978) assume that it is the consequence of conditions of the close binary formation as a result of which only binaries with $a \gtrsim 10\, R_\odot$ can form irrespectively of mass. Stars with the mass smaller than $\sim 1.5\, M_\odot$ have convective envelopes and probably the hot stellar wind. Such wind with magnetic field leads to effective orbital momentum loss and to gradual drawing together of components (Mestel, 1967). If it is so, the relative number of unevolved binaries with $M \lesssim 1.5\, M_\odot$ and $a \lesssim 10\, R_\odot$ must be lower than the number of wider systems. That is the case. Popova et al. (1980) found that the number of double-line spectroscopic binaries

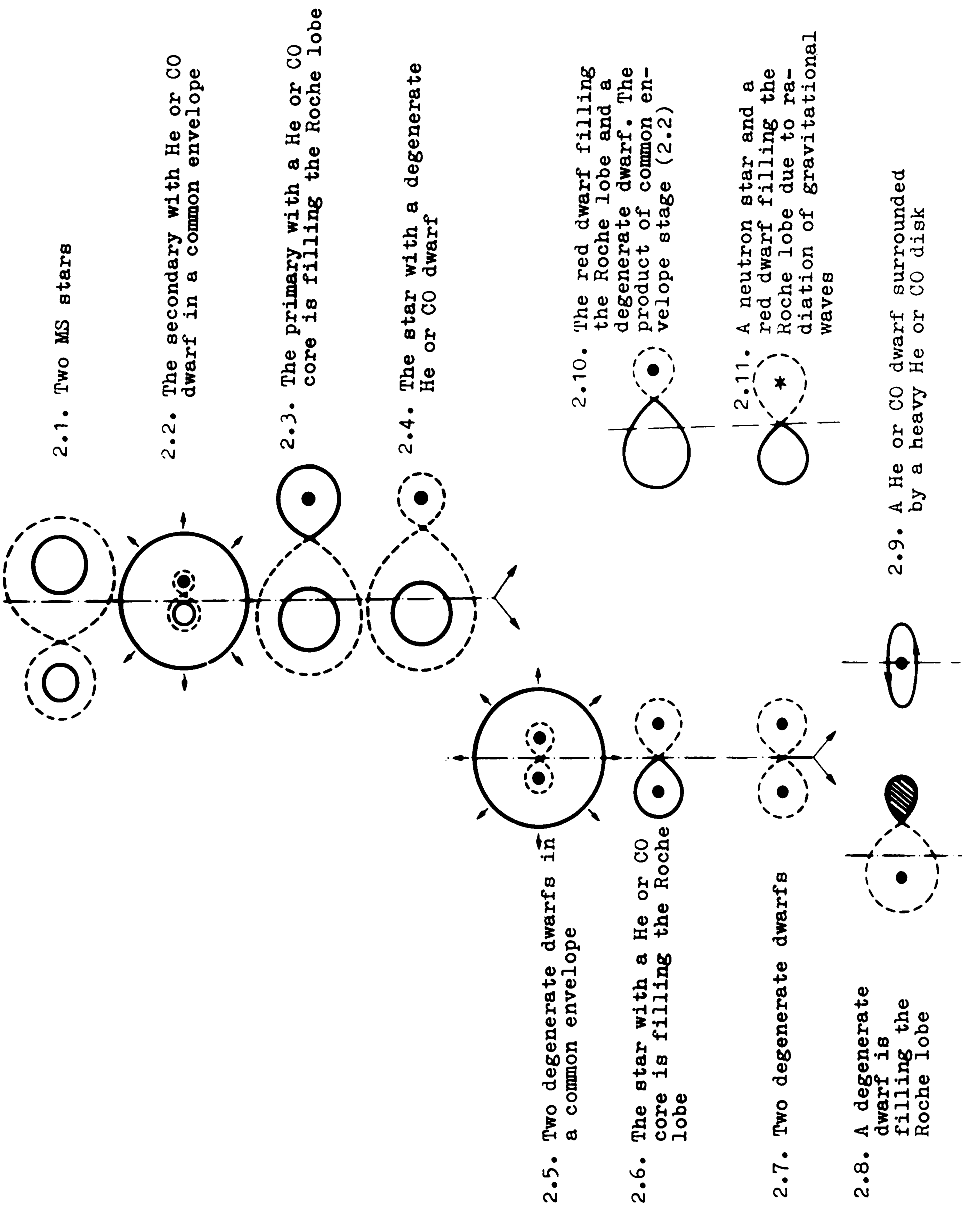

Fig. 2. Evolutionary scenarion for moderate mass close binaries ($1 \lesssim M_1/M_\odot \lesssim 10$).

with $0.6 \lesssim M/M_\odot \lesssim 1.5$ and $a \lesssim 15\, R_\odot M_\odot/M$ on unit of $\lg a$ is about ten times lower than the number of wider binaries which supports the possibility of such evolution of dwarf binaries having a component(s) with convective envelopes. If both components at the moment of contact stay unevolved, their merging could be a result of such evolution with "blue struggler" formation (Paczynski, 1979). Slightly evolved components form, possibly, WUMa systems. Properties and evolution of these stars have been reviewed extensively elsewhere (Binnendijk, 1977, Webbink, 1977, Shu et al., 1979).

The exhaustion of hydrogen in the nucleus of the primary leads as usually to expansion of the envelope and to the Roche lobe filling. Mass exchange in the thermal time scale of the primary can lead to the common envelope formation (2.2). If the system survives that stage, then after the partial loss of the primary envelope it becomes a helium or carbon-oxygen dwarf. If a low mass star filling the Roche lobe has the deep convective envelope, then very close cataclysmic variable like binary may form as a result owing to the extensive orbital momentum and mass loss (Webbink, 1979a; Meyer-Hoffmeister, 1979). As in the case of MCBS in the common envelope stage (Tutukov, Yungelson, 1979a) during the short time the drag luminosity exceeding the Eddington luminosity is possible as well. This leads to the extensive mass loss. The total lifetime of B and C systems in the semidetached stage (2.3.) is of the order of the thermal timescale of the expanding envelope. The system consisting of He or CO dwarf and a MS star forms as a result (2.4). The lifetime of low mass ($M \lesssim 3\, M_\odot$) B systems in (2.3) stage is determined by hydrogen burning of hydrogen rich envelope surrounding degenerate helium core (Paczynski, 1967). Probably, classical Algol type systems with the highly overluminous primary are the (2.3) systems. Analysis of observations of algols shows that prealgols are B-type systems mainly (Mezzetti et al., 1980). It is the natural result of the absence of A-type systems with the initial primary mass $1.5 \lesssim M/M_\odot \lesssim 10$ (Tutukov, Yungelson, 1980a). The exhaustion of the envelope's hydrogen or the central helium flash terminates the semidetached stage.

Mass and angular momentum loss can sometimes create rather close binaries but up to the Roche lobe filling the presence of the compact degenerate component is almost undiscoverable. It is possible that most part of single-line spectral binaries are such systems. The optical components of these systems may be "blue strugglers". One more possibility to distinguish such systems is the rotational velocity. Van den Heuvel (1968) found the bimodal distribution of stars over rotational velocity. It is possible that stars with low rotational velocities are hidden evolved binaries. If the initial mass of the primary was above $\sim 3\ M_\odot$ it produces a CO-dwarf. Helium shell flashes in its envelope can enrich it by heavy s-process product elements. Part of the envelope matter may be accreted during flashes by the secondary MS-component. That can help to understand the cause of some abundance anomalies of peculiar stars of spectral type A (Tutukov, Yungelson, 1980b).

If the system (2.4) is wide, the optical component may be a red (super)giant not filling its Roche lobe. Such cold stars lose the matter by stellar wind and a part of that matter is intercepted by the compact CO-dwarf. In this case the CO-dwarf reactivates its shell sources which keeps its luminosity on a rather high ($10^2 - 10^3\ L_\odot$) level for a long time. Hot radiation of dwarf ionizes part of the extended envelope of the red (super)giant. Instability of nuclear burning in partly degenerate shells supplements the symbiotic star model (Tutukov, Yungelson, 1976). The increase of the CO-dwarf mass can lead to supernova explosion and to the neutron star formation. XRS with lifetime of $\sim 10^6$ yrs may be a result of such evolution. And the radio pulsar in a wide system with low eccentricity forms. It is possible that radio pulsar in wide binaries like PSR0820+02 with $p \approx 1700^d$ and $e \approx 0$ (Manchester et al., 1980) was formed this way. But there is another possibility for such systems' formation: the capture in two body collisions between a red giant and a neutron star in dense globular clusters.

The expansion of optical component leads to the second mass transfer stage (2.4). All B-type systems with $M/T_{KH} \gtrsim 10^{-6}\ M_\odot$/yrs plunge into a common envelope (2.5). The evolution in that stage was studied by Meyer, Meyer-Hoffmeister (1979). The lifetime in that stage is of the order of the thermal time for the envelope. The fast friction leads to the high luminosity and to mass loss. The friction of the double core in the common envelope may lead, as in the MCBS case, either to a coalescence of degenerate cores or to the loss of common envelope. But in moderate mass binaries case the gravitational energy of two compact degenerate cores is so high that the envelope can be dispersed. The double core of the young planetary nebula like UU Sge according to Paczynski (1974) form as a result. Such cores were discovered by Miller et al. (1976). About 10^4 years later the envelope disperses and two degenerate cooling dwarfs remain. Such systems are also found now: V 471 Tau (Nelson and Young, 1970), PG 1413+0.1 (Green et al., 1978). The total number of similar systems (2.7) in our Galaxy is large ($\sim 10^{10}$) but the probability to find

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low luminous compact dwarfs is very low, so only the youngest and closest of them may be discovered.

If the initial mass of the optical component was lower than $\sim 3\ M_\odot$, then a rather long semidetached stage (2.6) is possible. Another possibility to have the high mass exchange rate in dwarf binaries is exchange in thermal time scale and, possibly, the strong magnetic stellar wind.

Three main types of instabilities involved in accretion are usually discussed: dynamical instability of the convective low mass component losing matter (Bath, 1975), disk accumulation (Osaki, 1974) and thermonuclear runaway (Lebedinsky, Gurevich, 1947). The disk accumulation instability leads to dwarf nova explosions if an accreting star is a degenerate and to X-ray recurrent nova like Aqu X-1 if it is a neutron star. If we suppose that $\sim 10\ \%$ of time Aqu X-1 radiates on the Eddington limit (Charles, 1980), then the average accretion rate is $\sim 10^{-9}\ M_\odot$/yrs, which is close to the accretion rate in dwarf novae and X-ray bursters. It is possible that some classical novae with the low ($\sim 10^{-9}\ M_\odot$/yrs) rate of the mass exchange may display the dwarf nova-like activity like nova GK Per (Webbink, 1977b). The analytical theory of nuclear burning in thin degenerate envelopes of compact stars was developed (Sugimoto et al., 1980, Ergma, Tutukov, 1980a,b) which gives a possibility to estimate some properties of bursting sources without extensive computations.

The numerical theory of novae is now well developed (Gallagher, Starrfield, 1978). The first computations were performed for models with the overabundance of CNO elements (Starrfield et al., 1972) which were supported by observations of novae (Pottasch, 1959). But pure thermonuclear explosion cannot lead to the loss of the envelope during the flash. To lose the hydrogen rich envelope an additional mass loss mechanism is needed, like the hot stellar wind or the common envelope stripping (Starrfield, 1980). The CNO overabundance can be produced by occurring from time to time helium shell flashes (Ergma, Tutukov, 1980b).

If the accreting star is an old cold neutron star, then recurrent thermonuclear X-ray bursts are possible (Marashi, Cavaliere, 1976). The simple analytical model explains energy, the period of repetition of X-ray bursters (Ergma, Tutukov, 1980), and numerical computations by Joss (1978) give the light curve of bursts. But the problem of chemical kinetics and possible deviation from spherical symmetry of the burning shell remains a problem under active investigation.

The growth of CO dwarf can lead to supernova explosion (Whelan, Iben, 1973, Ergma, Tutukov, 1976) with, possibly, a neutron star formation in pair with low mass component (2.11). But this is unlikely for recurrent novae because in the course of the nuclear flash only several percent of hydrogen can burn and be accumulated by CO-core. The common envelope stage (2.2), radiation of gravitational waves and the magnetic stellar wind may be important for orbital angular momentum loss. A close binary (2.10) forms as a result. Similar systems (2.10, 2.11) may be also formed after unelastic collisions (Fabian et al., 1975) or due to exchange collisions of a low-mass close binary with a degenerate dwarf (a neutron, a black hole) in dense nuclear of globular clusters according to Hills (1979). The accretion of the most part of the low mass component makes the collapse of a neutron star with black hole formation inevitable in some cases. It is possible that part of stationary bulge X-ray sources are in the post-burster stage and consist of a low mass black hole and low mass red dwarf components.

The model of the bulge source is an old neutron star with the red dwarf component filling its Roche lobe. The radiation of gravitational waves provides for mass exchange with the rate of $\sim 10^{-10} - 10^{-9}$ $M_\odot$/yrs which is well enough for keeping the X-ray luminosity $\sim 10^{36} - 10^{37}$ ergs/s (Tutukov, Yungelson, 1979b). The total number of such binaries formed in the Galaxy lifetime is $\sim 10^3$ and according to their space distribution most of them were formed in globular clusters and in galo (van den Heuvel, 1980). Evolution of these binaries whose secondaries fill their Roche lobes may be influenced by two specific peculiarities induced by the strong X-ray irradiation of optical components. One-side heating can lead to the circulation and to the mixing of the secondary and to the strong evolutionary meaningful stellar wind. Such evolution seems not studied numerically so far.

The evolution of systems consisting of two degenerate dwarfs or a degenerate dwarf and a neutron star (2.7) is possible in the cosmological timescale only due to gravitational radiation (Tutukov, Yungelson, 1979b) if the orbital period is $p(\text{hours}) \lesssim 13\,(M_1 M_2/M_\odot^2)^{3/8}((M_1+M_2)/M_\odot)^{-1/8}$. The component of lower mass has the larger radius and fills its Roche lobe first. If $0.6 \lesssim q \lesssim 1$, the expansion of the filling Roche lobe component is not accompanied by the proper expansion of the Roche lobe itself. So this dwarf may be destroyed in the limit of orbital time scale and the heavy disk surrounding the ex-primary forms as a result. Further evolution of such systems strongly depends on the effectivity of angular momentum transfer in the disk. If that process is so effective that $\dot{M} \gtrsim 10^{-6}$ $M_\odot$/yrs, the

extended helium or carbon-oxygen envelope may be formed. A single star forms as a result.

The gravitational wave radiation driven by evolution of 2.10, 2.11 systems was investigated by Faulkner (1974), Tutukov, Yungelson (1979b), White, Eggleton (1980). Gravitational wave radiation decreases the orbital period until the star losing mass is in thermal equilibrium or until its mass is more than $\sim 0.1\ M_{\odot}$. Further mass loss leads to expansion of secondary and as a consequence to increasing of the orbital period. Thus for binaries 2.10 and 2.11 evolving due to gravitational wave radiation there must exist the minimal orbital period $\sim 1^h$ (Paczynski, 1979b, Massevitch et al., 1980). It is remarkable that the minimal orbital period of cataclysmic variables really exists and is $\sim 82^m$ for WZ Sge. The existance of the minimal period may be considered as a good argument for gravitational wave radiation. But we need to point out now that magnetic stellar wind of the appropriate intensity influences dwarf binary evolution similarly. The well known absence of cataclysmic variables with $2^h \lesssim p \lesssim 3^h$ gives a good but still unused (as it seems) chance to advance the theory of dwarf binary evolution.

So the short review of modern theory of close binary evolution shows that the theory is now actively developed by astrophysicists of many countries. The process of advancing and selecting new ideas in the field is constantly supported by new observational data on the binaries in different evolutionary stages. Many types of stars are involved in investigation in connection with close binary evolution.

As a conclusion let me point out the main still unresolved problems related to close binary evolution. 1. Formation of close binaries and planetary system. Explanation of distribution of close binaries over mass of components, semiaxes and ratio of mass components. 2. Mass and orbital momentum loss during evolution of close binaries. 3. Evolutionary scenario for moderate mass close binaries ($M \lesssim 10\ M_{\odot}$). 4. Evolution in common envelope stages. 5. The stability of disk accretion, especially for dwarf close binaries.

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REFERENCES

Abt, H.A., Levy, S.G.: 1976, Astrophys.J.Suppl. 30, p.273.
Abt, H.A.: 1979, "The frequency of binaries on the main sequence", preprint.
Bath, G.T.: 1975, Month.N.R.A.S. 171, p.311.
Binnendijk, L.: 1977, Vistas in Astron. 21, p.359.
Charles, P.: 1980, Sky and Telescope 59, p. 188.
Chiosi, C., Suma, C.: 1970, Astrophys.Sp.Sci. 8, p.478.
Davidson, K., Ostriker, J.P.: 1973, Astrophys.J. 179, p.585.
Fabian, A., Pringle, J., Rees, M.: 1975, Month.N.R.A.S. 172, p.15.
Faulkner, J.: 1974, Proc. IAU Symp. 73, Eds. P. Eggleton, S. Mitton, J. Wheelan, p.193.
Gallagher, J.S., Starrfield, S.: 1978, Ann.Rev.Astron. Astrophys. 16, 171.
Gott III, J.R.: 1972, Astrophys.J. 173, p.227.
Green, R.F., Richstone, D.O., Schmidt, M.: 1978, Astrophys. J. 224, p.892.
Joss, P.C.: 1978, Astrophys.J.L. 225, L123.
Joss, P.C., Rappoport, S.: 1979, Astron. Astrophys. 71, p.217.
Habing, H.J.: 1977, Proc. IAU Coll. 42, Eds. R. Kippenhahn, J. Rahe, W. Stromeier, p.401.
Hanson, R.B.: 1979, Month.N.R.A.S. 186, p.357.
Helfand, D.J., Tademaru, E.: 1977, Astrophys. J. 216, p.842.
Hills, J.G.: 1975, Astron.J. 80, p.809.
Humphreys, R.M., Davidson, K.: 1979, Astrophys.J. 232, p.409.
Hutchings, J.B.: 1975, Astrophys.J. 200, p.122.
Ergma, E.V., Tutukov, A.V.: 1980a, Proc. IAU Symp. 88.
Ergma, E.V., Tutukov, A.V.: 1980b, Proc. IAU Coll. 53.
Kraitcheva, Z.T.: 1974, Nauch.Inform. 31, p.58.
Kraitcheva, Z.T., Popova, E.I., Tutukov, A.V., Yungelson, L.R.: 1978, Astron. Zh. 55, p.1176.
Lebedinsky, A.I., Gurevich, L.E.: 1947, Dokl.Akad.Nauk 55, No.9 (USSR, in Russian).
Lozinskaya, T.A., Tutukov, A.V.: 1980, Nauch.Inform.USSR Acad.Sci., No.49 (in press).
Meyer, F., Meyer-Hoffmeister, E.: 1979, Astron.Astrophys. 78, 167.
Manchester, R.N., Newton, L.M., Cooke, D.J., Lyne, A.G.: 1980, Astrophys.J.L. 236, L25.
Marashi, L., Cavaliere, A.: 1976, Highlights Astron. 4,p.127.
Mason, K.O.: 1977, Month.N.R.A.S. 178, p.81.
Massevitch, A.G., Tutukov, A.V., Yungelson, L.R.: 1976, Astrophys.Sp.Sci. 40, p.115.
Massevitch, A.G., Popova, E.I., Tutukov, A.V., Yungelson, L.R.: 1979, Astrophys.Sp.Sci. 62, p.451.
Massevitch, A.G., Tutukov, A.V.: 1980, "The star evolution", Moscow (in Russian).
Massevitch, A.G., Tutukov, A.V., Yungelson, L.R.: 1980, Proc. IAU Symp. 93.

Mestel, L.: 1967, Proc. Liège Coll., 1966, p.351.
Mezzetti, M., Ginricin, G., Mardirossian, F.: 1980, Astron. Astrophys. 83, p.217.
Miller, J.S., Krzeminski, W., Priedhorsky, W.: 1976, IAU Circ. No. 2974.
Moffat, A.F.J., Isserstedt, J.: 1979, "The Nature of Single-Line Population I Wolf-Rayet Stars: Evidence for High Space Velocity", preprint.
Nelson, B., Young, A.: 1970, Publ.Astron.Soc.Pac. 82, p.699.
Osaki, Y.: 1974, Publ.Astron.Soc.Japan 26, p.429.
Paczynski, B.: 1967, Acta Astron. 17, p.355.
Paczynski, B.: 1971, Ann.Rev.Astron.Astrophys. 9, p.183.
Paczynski, B.: 1974, private communication.
Paczynski, B.: 1979a, private communication.
Paczynski, B.: 1979b, review paper at IAU Assembly in Montreal, "Stellar evolution and close binaries".
Popova, E.I., Tutukov, A.V., Yungelson, L.R.: 1980(in prep).
Pottasch, S.: 1959, Ann.d'Astrophys., 22, p.412.
Shu, F.H., Lubow, S.H., Anderson, L.: 1979, Astrophys.J. 229, p. 223.
Starrfield, S., Truran, J.W., Sparks, W.M., Kutter, G.S.: 1972, Astrophys.J. 176, p.223.
Starrfield, S.: 1980, Proc. IAU Coll. 53, p.274.
Stone, R.C.: 1979, Astrophys.J. 232, p.520.
Sugimoto, D., Fujimoto, M.Y., Nariai , K., Nomoto, K.: 1980, Proc. IAU Coll. 53.
Svechnikov, M.A.: 1969, Catalog of orbital elements of close binaries, Sverdlovsk.
Taam, R.E., Bodenheimer, P., Ostriker, J.P.: 1978, Astrophys.J. 222, p.269.
Thomas, H.-C.: 1977, Ann.Rev.Astron.Astrophys. 15, p.127.
Thorne, K.S., Zytkow, A.: 1977, Astrophys.J. 212, p.832.
Tutukov. A.V., Yungelson, L.R.: 1971, Nauch.Inform. 20,p.86.
Tutukov, A.V., Yungelson, L.R.: 1973a, Nauch.Inform.27,p.58.
Tutukov, A.V., Yungelson, L.R.: 1973b, Nauch.Inform.27,p.70.
Tutukov, A.V., Yungelson, L.R., Kraitcheva, Z.T.: 1975, Mem.Soc.Astron.Ital. 45, p.879.
Tutukov, A.V., Yungelson, L.R.: 1976, Astrofizika 12, p.521.
Tutukov, A.V., Yungelson, L.R.: 1979a, Proc. IAU Symp. 83.
Tutukov, A.V., Yungelson, L.R.: 1979b, Acta Astron. 29, p.665.
Tutukov, A.V., Yungelson, L.R.: 1980a, Proc. IAU Symp. 88.
Tutukov, A.V., Yungelson, L.R.: 1980b, Nauch.Inform. 37 (in press).
Vanbeveren, D., Conti, P.S.: 1979, preprint.
Van den Heuvel, E.P.J.: 1968, Bull.Astron.Soc.Nether. 19, p.309.
Van den Heuvel, E.P.J., Heise, J.: 1972, Nat.Phys.Sci. 239, p.67.
Van den Heuvel, E.P.J.: 1976, Proc. IAU Symp. 73, p.35.
Van den Heuvel, E.P.J.: 1980, Proc. of Advanced Study Inst. "Extragalactic X-ray Astronomy".

Van den Heuvel, E.P.J., Ostriker, J.P., Patterson, J.A.: 1980, Astron.Astrophys. 81, p.7.
Yungelson, L.R.: 1973, Nauch.Inform. 27, p.93.
Yungelson, L.R., Massevitch, A.G.: 1980, "Mass exchange and evolution of close binary stars", Sov.Sci.Rev., Ed. R.A. Syunyaev.
Ziolkowski, J.: 1977, Ann.New-York Acad.Sci. 302, p.47.
Webbink, R.F.: 1977a, Astrophys.J. 215, p.851.
Webbink, R.F.: 1977b, Proc. IAU Coll. 42, Eds. R.Kippenhahn, J. Rahe, W. Stromeier, p.363.
Webbink, R.F.: 1979a, "The evolutionary significance of recurrent novae", preprint IAP-79-3, Illinois.
Webbink, R.F.: 1979b, "The formation of white dwarfs in close binary systems", preprint IAP-79-29, Illinois.
Wheaver, T.A., Woosley, S.E.: 1980, Bull.AAS 12, p.202.
Whelan, J., Iben, I.Jr.: 1973, Astrophys.J. 186, p.1007.
White, C.A., Eggleton, P.P.: 1980, Month.N.R.A.S. 190, p.801.

DISCUSSION

Chen: Consideration of the evolution of close binaries usually begins with two main-sequence stars. How could two stars with quite different masses be on the main sequence at about the same time?

Tutukov: The nuclear timescale and the Kelvin-Helmholtz timescale are so different, and the nuclear timescale depends on the mass of the star so strongly, that I hope there are no problems in having two main sequence components.

Sugimoto: Do you claim that a common envelope binary is more likely than mass loss from the system? If so, what is the reason, and how long are the timescales for formation of the common envelope and for mass loss?

Tutukov: I think now that the common envelope stage is unavoidable, at least for wide B and C systems. The reason is the following. The expansion of an evolved star occurs on the thermal timescale of its envelope, and one usually needs several additional thermal timescales to achieve solid body rotation. Only for such a rigidly rotating system is it possible to lose excess mass from the system. Therefore, the first stage of common envelope evolution will persist at least several thermal timescales. But when a compact body plunges into the deep interior, there are processes that likely occur faster—on timescales between the thermal and the orbital timescales. (For details, see Tutukov and Yungelson in Proc. IAU Symp. No. 83.)

Vilhu: Can you identify any good candidates where "spiralling in" is now occurring, or will soon occur?

Tutukov: Possible candidates where "spiralling in" will soon occur are massive close-binary X-ray sources. Possible candidates for the common envelope stage are P Cyg, η Car. Possible candidates for the post spiralling-in stage are cataclysmic variables and single-line WR stars of the WN types that lie inside remnants with expanding nebulosities.

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