EVOLUTION OF MASSIVE COMMON ENVELOPE BINARIES AND MASS LOSS

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ABSTRACT

A way of treatment of evolution of common envelope binaries based only on the laws of conservation of energy and angular momentum is suggested. It is shown that the final configuration depends on masses of components and initial period of the system, and on parameters describing friction in the envelope, and mass loss by the system. Possible final stages for massive binaries are either a Thorne-Zytkow type object for initially close binaries or a Wolf-Rayet star in pair with a relativistic compact remnant for wider ones. In the course of disruption of the latter system with orbital periods up to several hours very high space velocity (up to 500 km/s) pulsars can arise.

1. INTRODUCTION

The common envelope stage in the course of evolution of close binaries seems inevitable if we try to explain the origin of such objects as double cores of planetary nebulae, binary radio-pulsar, cataclysmic binaries, X-ray sources, because all of them probably lose the excess of mass and angular momentum of progenitor systems by mass loss from common envelopes. Also, from purely theoretical point, as was shown by Benson (1970) and Yungelson (1973), a common envelope binary inevitably forms if in a binary system the time-scale of mass exchange is shorter than the thermal time-scale of the accreting component.

The quantitative investigation of common envelope binary evolution is extremely complicated, as a lot of processes lack not only appropriate mathematical description, but even a precise physical formulation. Let us name some of them: friction between the envelope and the double

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core; generation of acoustic waves in the common envelope and their transformation into the shock waves in the upper part of the atmosphere; mixing of the matter in the envelope; mass loss by the system; tidal effects.

Below we suggest a simplified treatment of the common envelope binaries problem, based only on conservation laws for energy and angular momentum and on assumption that the momentum exchange between layers of a star does not occur, on the short thermal time-scale at least. The latter assumption is not valid when the secondary is in the convective part of the common envelope.

2. FORMULATION OF THE PROBLEM

We shall discuss a system consisting of a (super)giant and a compact object -- unevolved main sequence star, white dwarf or neutron star with initial mass ratio exceeding, say 3. We assume that the preceeding evolution of such systems follows the simple scenario outlined, e.g. by Paczyński (1971) or Massevitch et al. (1976). The zero-point of our discussion is the instant when the giant has overflowed the Roche lobe and just engulfed the compact object (CO). CO is surrounded by an accretion disc supported by mass transfer from the primary. We shall ignore the increase of the CO mass, which is insignificant during the period of existence of the common envelope that is close to the thermal time-scale. We assume in this paper that the radius of interaction of CO and the giant envelope is equal to the radius of CO lobe of Roche surface. We do not take into account the momentum exchange between orbital motion and axial rotation.

The orbital angular momentum of the system is

$$\mathcal{L} = G^{\frac{1}{2}} M_r m R^{\frac{1}{2}} / (M_r + m)^{\frac{1}{2}} \tag{1}$$

where M_r is the mass of the giant inside the orbit of CO with mass m, R -- distance between the centers of stars. If CO accelerates the resting element of the giant envelope to the angular velocity $\varphi\omega$, where ω is the Keplerian angular velocity of CO, $\varphi \leq 1$, then the moment transferred from CO to the giant per unit time is

$$\dot{j} = \alpha \dot{M}_r \varphi \omega R^2 M_r^2 / (M_r + m)^2 \tag{2}$$

where $\dot{M}_r$ is amount of matter passing through the orbit of CO per unit time: $\dot{M}_r = 4\pi\rho R^2 (\dot{R} - v)$, where v is the velocity of evolutionary expansion of the giant. If the system rotates rigidly, $\alpha \approx 2/3$, but varying α one may vary the efficiency of momentum transfer. Within our assumptions the only source of $\dot{j}$ is the orbital angular momentum. Then, differentiating (1) and equating the derivative to $\dot{j}$, we get

$$\dot{R}/R = \dot{M}_r/M_r \left[\frac{2\alpha\varphi M_r^2}{m(M_r+m)} + \frac{M_r}{M_r+m} - 2 \right] . \qquad (3)$$

Placing (2) into (3) and substituting variables: $y = M_r/4\pi\rho R^3$, $x = M_r/m$, where ρ is density, we get

$$\dot{R} = - \frac{v}{\dfrac{y}{\left[\dfrac{2\alpha\varphi x^2}{x(1+x)} + \dfrac{x}{1+x} - 2\right]} - 1} . \qquad (4)$$

Assuming that the force of friction is proportional to the square of relative velocity we get that the transfer of momentum from CO to the spherical layer of the giant envelope is described by the equation

$$\gamma\rho(1-\varphi)^2\omega^2 R^5 = \alpha \dot{M}_r \varphi\omega R^2 , \qquad (5)$$

where the parameter γ depends mainly on the coefficient of friction and on geometrical cross-section of interaction. We can transform equation (5) into

$$\varphi = (1+\delta)\left(1-\sqrt{1-1/(1+\delta)^2}\right) , \qquad (6)$$

where $2\delta = \alpha y \dot{M}_r/(\gamma\omega M_r)$ is by order of magnitude equal to the quotient of division of orbital period by the time-scale of evolutionary expansion of the giant. In the beginning of the common envelope stage CO moves in the low density layers and is able to effectively transfer angular momentum — φ is close to 1.

As the momentum is lost, CO moves into denser layers of the giant. The former interacts now with layers with large momentum of inertia. The momentum of CO is not high enough to accelerate these layers up to the velocity of CO. Because of this the loss of momentum and matter from the envelope selfaccelerates and further proceeds in the dynamical time-scale (CO "falls through the giant"). The same is true if CO moves in the convective layers of the common envelope. In this case evolutionary expansion of the giant does not play any role and from the condition of conservation of angular momentum it follows that

$$\varphi = (y+2)/(2\alpha x^2) + (y+1)/(2\alpha x) . \qquad (7)$$

Formally (7) is equivalent to the turning into 0 of the denumerator of (4). The boundary corresponding to the transition into "fall"-regime is marked by letter A in Figure 1.

If the geometrical cross-section of interaction is not fixed as now, but is determined by ram pressure, then its variations due to relative motion of CO and gas of the envelope may control the process of angular momentum

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transfer and the dynamical "fall"-stage may proceed rather slowly. It is possible that extremely luminous η Car and P Cyg type objects with very high mass loss rates are examples of binaries passing through such "slow fall" stage.

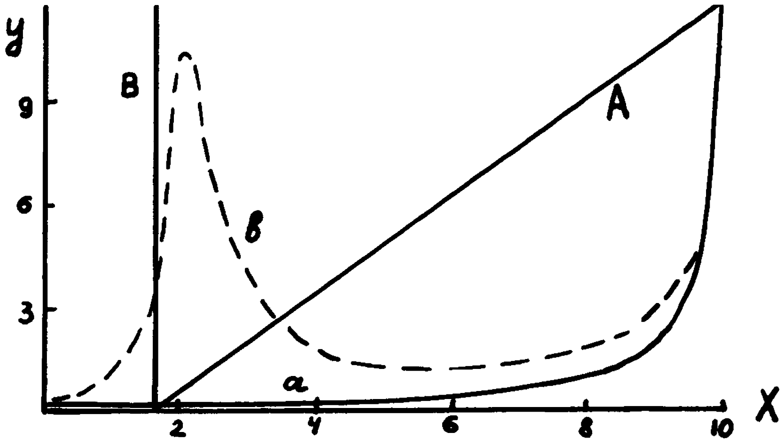

Figure 1. x-y plane. a — curve corresponding to ZAMS star 10M b — evolved $\log T_e = 3.6$, $10 M_\odot$ star, A,B — lines dividing regions of different regimes of spiral-in.

In the densest layers of the giant that experience expansion due to nuclear burning it is possible that CO moves away from the center. The right-side border of this region in the x-y plane is defined by the equation $2\alpha\varphi x^2/(1+x) + x/(1+x) - 2 =$ that formally corresponds to the turning into 0 of the right-side part of (3). In Fig. 1 the curve determined by the above equation for the case $\varphi=1$ is marked as B.

The observational appearance and final configuration of systems with common envelopes depend on mass loss. Movement of a double core in a common envelope generates acoustic waves, which, propagating outward, transform into shock waves, heat the envelope and cause coronal-type mass loss. We assume that part β of gravitational orbital energy is spent on mass loss, but part $(1-\beta)$ is given off in layers immediately surrounding CO. Thus we introduce into the discussion an additional "shell-source" of energy with luminosity $L_{sh} = \ell_* + (1-\beta) G M_r \dot{R}/2/R^2$, where ℓ_* is the sum of the own luminosity of CO and the accretion-generated luminosity (equal to the critical luminosity in the upper limit). Thus the problem of evolution of common envelope binaries is completely defined by 3 parameters α, β, γ.

Let us get estimates concerning the fate of common envelope systems. Gravitational energy liberated when CO moves from the surface of the red giant to the surface of its helium core is $0.5\beta G M_{He} m/R_{He}$. Energy necessary for ejecting of the envelope is $\psi GM^2/R$, where $\psi \approx 0.5$, because our computations show that dynamical "fall"-stage begins when the radius of the star is approximately two times greater than at the moment of contact of CO and the giant. If $0.5\beta G M_{He}/R_{He} > \psi GM^2/R$, the envelope is dispersed before the compact object reaches the boundary of the helium core. The final system is then a double core surrounded by loose remnants of the giant envelope (a double nucleus of a planetary nebula for small mass stars). For hydrogen-shell burning stars with $M \gtrsim 10 M_\odot$, $L_*/L_\odot = 10^2 (M_*/M_\odot)^{2.15}$ (Popova et al., 1978), and $R_{He}/R_\odot = 10^{-0.75}(M_{He}/M_\odot)^{0.64}$ for helium cores (Tutukov et al., 1973). This allows us to transform the above condition for energy to

$$T_e^* \lesssim (\beta/\psi)^{0.5} 10^{4.5} (L_\odot/L_*)^{0.1} (m/M_\odot)^{0.5} . \qquad (8)$$

Curves determined by (8) for $m = M_\odot$ and $m = 2M_\odot$ and $\beta = 1$, $\psi = 0.5$ are drawn in Fig. 2 along with evolutionary tracks for massive stars (Popova et al., 1978). If $m/M_\odot = 10^{-1.2} M_0/M_\odot$, where M_0 is initial mass of a star (Tutukov and Yungelson, 1973), and $\beta = 1$, $\psi = 0.5$, we obtain the curve drawn in Fig. 2 by dashed line. If at the instant of

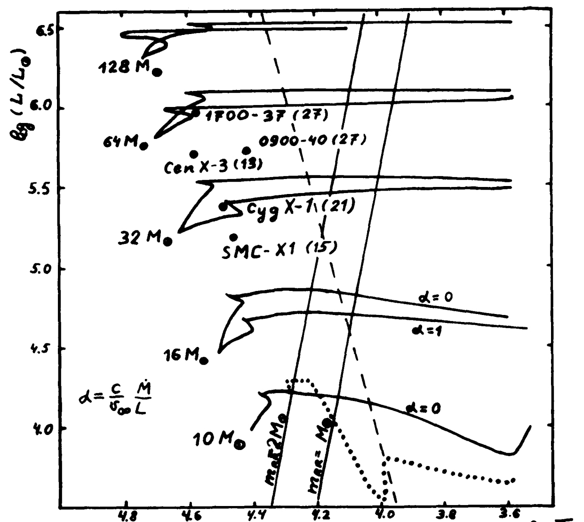

Figure 2. Evolutionary tracks of massive stars in plane. Positions of optical components of some X-ray binaries are marked. The numbers are their masses in solar units.

formation of a common envelope $T_e > T_e^*$, nuclei of the system will merge giving birth to a Thorne-Zytkow-type (1977) object. Lifetime of such objects is probably limited by mass overflow from the envelope and is unlikely to be higher than

10^7 years. Otherwise we should see $\sim 10^2$ times more red or infrared supergiants. Systems with $T_e < T_e^*$ will evolve into systems containing a hot helium star (like Wolf-Rayet stars) with a compact companion. Orbital periods of such binaries are of the order of several hours or days. Supernova explosion and disruption of the system gives birth to two single pulsars with spatial velocities up to ~ 500 km/s as the highest velocity observed for pulsars. Order of magnitude estimates are confirmed by the results of evolutionary computations of the common envelope binary $10 M_\odot + 1 M_\odot$ (Fig. 2). CO was a white dwarf with the own luminosity $\ell_* = 3{,}10^3 L_\odot$, $\beta = 0.5$. The computations were performed according to the procedure outlined above. In agreement with the above considerations three evolutionary phases were distinguished: the first -- slow, the second -- fast, the third -- again slow. In the last model computed CO was in the layer $M_r \approx 2 M_\odot$ $R \approx R_\odot$, mass of the giant was $7 M_\odot$. The amount of released gravitational energy was not great enough to disperse the whole envelope. The further evolution of the system will be determined by diffusion of angular momentum from the double nucleus (that was not considered in this paper).

In Fig. 2 positions of optical counterparts of some X-ray sources, according to Conti (1977), are marked. As indicated by position of stars relative to the dashed curve in Fig. 1, stars constituting the X-ray systems can merge.

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DISCUSSION FOLLOWING TUTUKOV and YUNGELSON

Underhill: About 4 years ago Stecher and Sparks suggested that the infall of a white dwarf companion of a red giant might cause a supernova explosion. Do your more detailed results support their conclusions?

Tutukov: In the frame of our local approach the process of "spiral in" occurs on a thermal time scale mainly, and the orbits of the core's components remain close to ring. Only part of evolution can proceed on a time scale comparable with a dynamical one. But we hope that the selfadjustment of effectiveness of the momentum loss process by ram pressure can slow down the "spiral in" during that stage. The existence of the binary pulsar supports our hope that "peaceful coexistence" of the components of the double core inside a supergiant is possible in some cases at least.

Bidelman: For some time I have been wondering whether the old hypothesis that cepheid variables are actually close double stars should be resurrected.Recent investigations of common-envelope binaries make this a far more attractive idea than in the past. I think it is now well worthy of theoretical investigation.

Dearborn: When the compact object spirals in, and transfers angular momentum to the envelope, it may produce a rapidly rotating star. Do your calculations indicate whether this effect will be large enough to be observable.

Tutukov: The compact object spirals down in the expanding envelope of a supergiant with the increasing moment of inertia of its envelope. So during this stage this conversion of the orbital angular momentum into rotational angular momentum almost does not influence the rotational velocity. If in the red supergiant stage at least a part of the rigidly rotating convective envelope is lost, the excess of angular momentum will be lost too. But if the angular momentum loss is not so effective, then it would be possible to find blue supergiants with an excessively high velocity of rotation.