Chin. J. Astron. Astrophys. Vol. 7 (2007), No. 2, 235–244
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

On the Physical Processes in Contact Binary Systems *

Run-Qian Huang[1], Han-Feng Song[1,2] and Shao-Lan Bi[1]

[1] National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011; *rqhuang@ynao.ac.cn*

[2] Graduate University of Chinese Academy of Sciences, Beijing 100049

Received 2006 July 3; accepted 2006 December 30

Abstract Three important physical processes occurring in contact binary systems are studied. The first one is the effect of spin, orbital rotation and tide on the structure of the components, which includes also the effect of meridian circulation on the mixing of the chemical elements in the components. The second one is the mass and energy exchange between the components. To describe the energy exchange, a new approach is introduced based on the understanding that the exchange is due to the release of the potential, kinetic and thermal energy of the exchanged mass. The third is the loss of mass and angular momentum through the outer Lagrangian point. The rate of mass loss and the angular momentum carried away by the lost mass are discussed. To show the effects of these processes, we follow the evolution of a binary system consisting of a $12M_{\odot}$ and a $5M_{\odot}$ star with mass exchange between the components and mass loss via the outer Lagrangian point, both with and without considering the effects of rotation and tide. The result shows that the effect of rotation and tide advances the start of the semi-detached and the contact phases, and delays the end of the hydrogen-burning phase of the primary. Furthermore, it can change not only the occurrence of mass and angular momentum loss via the outer Lagrangian point, but also the contact or semi-contact status of the system. Thus, this effect can result in the special phenomenon of short-term variations occurring over a slow increase of the orbital period. The occurrence of mass and angular momentum loss via the outer Lagrangian point can affect the orbital period of the system significantly, but this process can be influenced, even suppressed out by the effect of rotation and tide. The mass and energy exchange occurs in the common envelope. The net result of the mass exchange process is a mass transfer from the primary to the secondary during the whole contact phase.

Key words: stars: binaries: general — stars: mass-loss — stars: evolution

1 INTRODUCTION

Contact binaries are binaries where both components have filled their Roche lobes. Due to their small separation, the gravitational force from the primary or the secondary is strong enough to accrete matter from the surface of the other star. Thus, the two components have a common envelope and exchange of mass and energy operates to and fro between them. For contact binaries, there exist not only the spin of the components, but also the orbital rotation and the tidal action from the companion star. Due to the effects of rotation and tide, the shape of the components changes from spherical symmetric to non-spherical symmetric. Due to the effect of rotation, meridian circulation arises, transporting the chemical elements. In addition, a special form of mass and angular momentum loss via the outer Lagrangian point may occur, that may influence the orbital evolution of the system significantly. The structure and evolution of a contact binary depend mainly on the initial masses and initial chemical compositions of the components, and the

* Supported by the National Natural Science Foundation of China.

initial orbital separation between the components, but are also affected by the above mentioned physical processes. There have been quite a few studies on the structure and evolution of contact binaries using different models for those processes (e.g., Hazlehurst & Meyer-Hofmeister 1973; Robertson & Eggleton 1977; Hazlehurst & Refsdal 1980, 1984; Eggleton 1983; Kähler et al. 1986; Li et al. 2004a, b, 2005).

Specifics of these studies are: a) The effect of the spin of the components on the stellar structure equations has been studied (e.g. Eggleton 1983; Li et al. 2004a, b, 2005). b) There are different ways to approximate the energy exchange between the components. Some studies estimated the energy exchange by using the mass-luminosity relation validated for the W UMa-type contact binaries (e.g. Robertson & Eggleton 1977; Rahunen 1981; Li et al. 2004a, b, 2005). Another approach to the energy exchange issue is based on the understanding that the energy exchange is related to the entropy difference and the contact depth between the components (e.g., Hazlehurst & Meyer-Hofmeister 1973; Kähler et al. 1986). c) The effect of angular momentum loss due to the magnetic braking on the evolution of the W UMa-type contact binaries has been studied (Li et al. 2004a, b).

The purpose of the present paper is to study the physical processes occurring in contact binaries with the following emphases: a) The effect of the spin of the components, the orbital rotation and the tide on the stellar structure equations, as well as the effect of meridian circulation on the mixing of the chemical elements are considered simultaneously (Section 2). b) The energy exchange between the components is studied based on the understanding that the energy exchange is due to the release of the potential, kinetic, and thermal energy by the exchanged mass (Section 4). c) As a special form of the mass and angular momentum loss occurring in contact binaries, the loss through the outer Lagrangian point is studied (Section 5). d) In order to show the effects of these physical processes on the evolution of the contact binary we follow the evolution of a massive system consisting of a $12M_{\odot}$ and a $5M_{\odot}$ star with mass and energy exchange between the components, mass loss via the outer Lagrangian point and the effect of rotation and tide, and discuss the results obtained (Section 6).

2 THE EFFECT OF ROTATION AND TIDE

For the components of a binary system, there exist not only the spin of the components, but also the orbital rotation and the gravitational action from the companion star (the tidal action). Two effects of the rotation and tide are essential. The first is that the structure of the components is changed from spherical symmetric to non-spherical symmetric by the centrifugal and tidal forces. The second is the occurrence of the meridian circulation in the components, which results in the mixing of the chemical elements (see Huang 2004).

2.1 The Equipotentials of the Components

The potential for a synchronous rotating component in a Roche model is given by

$$\Psi_p = -\frac{GM_1}{r_i} - \frac{1}{2}\omega^2 r_i^2 \sin^2\theta - \frac{1}{2}\omega^2(X_\omega - r_i\sin\theta)^2 - \frac{GM_2}{\sqrt{(A - r_i\sin\theta)^2 + r_i^2\cos^2\theta}}\,, \qquad (1)$$

where M_1 and M_2 are the masses of the primary and the secondary, respectively, A is the orbital separation between the two, X_ω is the distance between the primary and the rotation axis of the system, and ω is the orbital angular velocity of the system. The coordinate system is shown in Figure 1. The first and second terms on the right side of Equation (1) correspond to the contribution from the gravitation and the spin of the components, respectively. The third and fourth terms correspond to the contribution from the orbital rotation of the system and the tidal action, respectively. From Equation (1), the equipotentials of the components defined by the equation Ψ =constant are non-symmetric rotational ellipsoids with two semi-major axes a_1 and a_2 ($a_1 > a_2$) and one semi-minor axis b (see Fig. 1 and Huang 2004).

2.2 The Stellar Structure Equations

Due to the effect of tide, the spin of the component is synchronous with the orbital motion of the system. Such synchronous rotation exists also in the interior of the components. Thus, the rotation of the components is solid-body rotation and can be called "conservative rotation". Kippenhahn & Thomas (1970) introduced a method to simplify the two-dimensional model with conservative rotation to a one-dimensional model

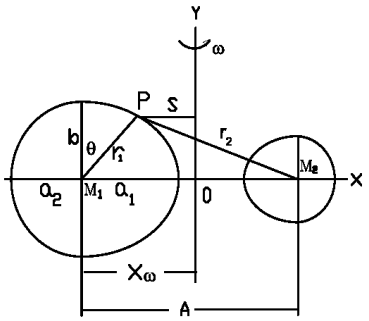

Fig. 1 Geometry for the calculation of the potential of the components.

and gave the following structure equations:

$$\frac{dr_\Psi}{dM_\Psi} = \frac{1}{4\pi r_\Psi^2 \rho}, \tag{2}$$

$$\frac{dP}{dM_\psi} = -\frac{GM_\Psi}{4\pi r_\Psi^2} f_P, \tag{3}$$

$$\frac{dL}{dM_\Psi} = \varepsilon_N - \varepsilon_\nu + \varepsilon_g, \tag{4}$$

$$\frac{d\ln T}{d\ln P} = \begin{cases} \nabla_{\rm R} f_{\rm T}/f_{\rm p} \\ \nabla_{\rm con} \end{cases}, \tag{5}$$

where

$$f_P = \frac{4\pi r_\Psi^4}{GM_\Psi S_\Psi} \frac{1}{\langle g_{\rm eff}^{-1}\rangle}, \tag{6}$$

$$f_T = \left(\frac{4\pi r_\Psi^2}{S_\Psi}\right)^2 \frac{1}{\langle g_{\rm eff}\rangle \langle g_{\rm eff}^{-1}\rangle}, \tag{7}$$

$$\nabla_{\rm R} = \frac{3\kappa LP}{4acGM_\Psi T^4}, \tag{8}$$

where, $\langle g_{\rm eff}\rangle$, $\langle g_{\rm eff}^{-1}\rangle$ are the mean values of the effective gravity and its inverse over the equipotential surface, respectively; $\nabla_{\rm R}$ the radiative temperature gradient.

2.3 Rotational Mixing

The rotation of the components results in an outward mass-flow along the rotational axis and an inward mass-flow in the equatorial plane. Such outward and inward mass flows in a star are called "the meridian circulation" (Kippenhahn & Weigert 1990; Maeder & Meynet 2000). As a result of the meridian circulation and the shear turbulence, a radial mass exchange occurs which can drive the transport of chemical elements in rotating stars. For the components in solid-body rotation there exists no differential rotation that can drive shear turbulence. Hence, the rotational mixing in the components of a binary system can be driven only by the effect of meridian circulation. Because the transport of the chemical elements is caused by the effect of rotation, and the effect of rotation of a mass layer can be approximated by the ratio of the mean effective gravity $\langle g_{\rm eff}\rangle_i$ to the gravity of this layer, the change of the composition of element α via a diffusion-advection process can be expressed as:

$$\left(\frac{\partial X_\alpha}{\partial t}\right)_r = \left(\frac{\partial}{\partial r}\right)_t \left[-D_{\rm adv}\frac{\langle g_{\rm eff}\rangle_i}{g_i} - D_{\rm diff}\left(\frac{\partial X_\alpha}{\partial r}\right)_t\right] + \left(\frac{dX_\alpha}{dt}\right)_{\rm nuc}, \tag{9}$$

where $D_{\rm adv}$ and $D_{\rm diff}$ are two coefficients ($D_{\rm adv} = \frac{K_1}{\tau_{\rm adv}}$, $D_{\rm diff} = \frac{K_2}{\tau_{\rm th}}$), K_1 and K_2 are dimensionless parameters. The thermal and the advection time-scales can be given as (see Maeder & Meynet 2000; Huang & Yu 1998): $\tau_{\rm th} = \frac{1}{2}q\frac{GM^2}{RL}$ and $\tau_{\rm adv} = \tau_{\rm th}\frac{GM}{R^3\omega^2}$. The last term of Equation (9) is the change of composition due to nuclear reactions. At the inner and outer boundaries reflecting conditions are used:

$$\left(\frac{\partial X_\alpha}{\partial r}\right)_t |_{r=0} = 0 = \left(\frac{\partial X_\alpha}{\partial r}\right)_t |_{r=R} \,. \tag{10}$$

3 MASS EXCHANGE BETWEEN THE COMPONENTS

3.1 Conditions for Mass Exchange

There are two physical processes which affect the mass exchange between the components. The first is the transfer of mass in the common envelope, when the average potential of the primary $\bar{\Psi}_1$ differs from that of the secondary $\bar{\Psi}_2$. The second is the change of the inner state of the components (includes the transfer of mass and energy between the inner and outer layers and the expansion or contraction of the components), as soon as mass flow takes place in the common envelope. As a result of the mass transfer in the common envelope and the change of the state of the components, the average potentials of the primary and the secondary are changed. If the changed average potentials not equal, then the mass exchange between the components continues:

$$\begin{array}{lll} \text{If} & \bar{\Psi}_1 > \bar{\Psi}_2, & \text{mass flows from primary to secondary,} \\ \text{If} & \bar{\Psi}_1 < \bar{\Psi}_2, & \text{mass flows from the secondary to the primary.} \end{array} \tag{11}$$

The condition for the mass exchange to terminate is

$$\bar{\Psi}_1 = \bar{\Psi}_2. \tag{12}$$

The time scale of the mass transfer process (from the beginning of the mass transfer in the common envelope to when the condition $\bar{\Psi}_1 = \bar{\Psi}_2$ is satisfied) is, however, very short compared to that of the contact phase.

3.2 The Rate of Mass Transfer

There are two ways to calculate the rate of mass transfer between the components in the envelope: The first one is the theoretical calculation based on the requirement that the average potentials of the primary and the secondary are equal after the mass exchange. This theoretical calculation is, however, complicated. The second way is an approximate calculation using an adjustable parameter. We approximate the mass exchange rate as:

$$\begin{array}{ll} \frac{dM_{1c}}{dt} = -CM_1(\bar{\Psi}_1 - \bar{\Psi}_2), & \text{mass flows from primary to secondary,} \\ \frac{dM_{2c}}{dt} = -\frac{dM_{1c}}{dt}, & \end{array} \tag{13}$$

where the constant C is an adjustable parameter. The physical condition of Equation (13) is that the mass exchange rate is determined by the requirement that the average potentials of the primary and the secondary should be equal after the mass transfer. Thus, the rate of mass transfer is related to the difference between the average potentials of the two components before the mass transfer. Furthermore, the effect of the total mass on the rate of mass exchange is also considered in the equation.

The following cases can occur when the mass transfer rate is calculated with Equation (13): If the chosen value of the parameter C is very small, and the condition of $\bar{\Psi}_1 > \bar{\Psi}_2$ exists both before and after the mass transfer, then mass transfer from the primary to the secondary must happen several times before the condition $\bar{\Psi}_1 = \bar{\Psi}_2$ is satisfied. In the contrary case, if the chosen value of the parameter C is very large, and we have $\bar{\Psi}_1 > \bar{\Psi}_2$ before the mass transfer and $\bar{\Psi}_1 < \bar{\Psi}_2$ after then mass transfer will continue back and forth between the two componenets until the equilibrium is established. An extreme case occurs when the transferred mass is so large that the potential of the donor component falls below that of the inner Lagrangian point, and the binary system changes from a contact system to a semi-contact one.

4 THE ENERGY EXCHANGE

A model to treat the energy exchange is presented based on the understanding that the energy exchange is due to the release of potential, kinetic and thermal energy of the exchanged mass. Thus, the two processes of energy transfer and mass transfer are closely related.

4.1 Release of Potential Energy

It is assumed that the exchanged mass ΔM_{1c} is distributed inside a shell on the surface of the primary before the transfer, and within a shell on the surface of the secondary after the transfer. The release of potential energy due to the flow of ΔM_{1c} from the surface of the primary to the surface of the secondary is:

$$\Delta E_P = \Delta M_{1c} \times (\bar{\Psi}_1 - \bar{\Psi}_2). \tag{14}$$

4.2 Release of Kinetic Energy

We assume as above the location of the exchanged mass ΔM_{1c} before and after the exchange. If the shells are approximated as rigid bodies, then the rotational kinetic energy so released is:

$$\Delta E_K = \Delta M_{1c}\Big\{\frac{1}{2}\Big(\frac{2}{3}R_1^2 + X_\omega^2\Big) - \frac{1}{2}\Big[\frac{2}{3}R_2^2 + (A - X_\omega)^2\Big]\Big\}\omega^2, \tag{15}$$

X_ω being the distance between the primary and the mass center of the system and ω, the angular velocity of the system. The terms $[\frac{2}{3}R_1^2 + X_\omega^2] \times \Delta M_{1c}$ and $[\frac{2}{3}R_2^2 + (A - X_\omega)^2] \times \Delta M_{1c}$ are the moments of inertia of the two shells.

4.3 Release of Thermal Energy

There are two physical processes that affect the thermal conditions of the outer layers of the components. The first one is the transfer of mass and energy in the common envelope, which tends to equalize the effective temperatures of the two components. The second one is the transfer of mass and energy between the inner and outer layers of the components when mass exchange between the components takes place. This process changes once again the thermal conditions of the outer layers of the components, resulting in a new difference between the effective temperatures of the components. The timescales of those two processes are important. As mentioned above, the exchanged mass ΔM_{1c} is distributed within a shell on the surface of the primary before the transfer and within a shell on the surface of the secondary after the transfer, and the effective temperatures of the primary and the secondary, $T_{\rm eff1}$ and $T_{\rm eff2}$, are different. The release of thermal energy in this process can be expressed as:

$$\Delta E_T = \Delta M_{1c}\Big(\frac{3kT_{\rm eff1}}{2\mu_1 m_p} - \frac{3kT_{\rm eff2}}{2\mu_2 m_p}\Big), \tag{16}$$

where μ_1 and μ_2 being the mean molecular weights of the two components, and m_p, the proton mass. Equation (16) includes the case of no thermal energy exchange ($\Delta E_T = 0$), when the two effective temperatures are equal.

4.4 The Energy Exchange

The total amount of energy exchange due to the release of different forms of energy is:

$$\Delta E_c = \Delta E_p + \Delta E_k + \Delta E_T. \tag{17}$$

According to the virial theorem, half of the exchanged energy will be converted into the luminosity and the rest will be converted into the thermal energy of the components. Because the release of potential energy, the release of kinetic energy and the contact depth are all related to the orbital separation between the components, the release of potential and kinetic energy is, therefore, related to the contact depth. Furthermore, the release of the thermal energy is related to the entropy difference between the components. Hence, the understanding, that the energy exchange is due to the release of potential, kinetic and thermal energy of the exchanged mass, supports the opinion that the energy exchange is related to the entropy difference and contact depth (see Hazlehurst & Meyer-Hofmeister 1973; Kähler et al. 1986).

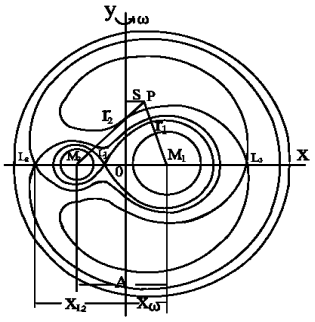

Fig. 2 Geometry for the calculation of the potential at the outer Lagrangian point.

5 MASS AND ANGULAR MOMENTUM LOSS FROM THE OUTER LAGRANGIAN POINT

5.1 Potential of the Outer Lagrangian Point L_2

Figure 2 shows the Roche equipotential surface passing through the outer Lagrangian point L_2. According to Equation (1), the potential at this point is:

$$\Psi_{L2} = \begin{cases} -\frac{GM_1}{X_{L_2}+X_\omega} - \frac{GM_2}{X_{L_2}+X_\omega-A} - \frac{1}{2}\omega^2 \times X_{L_2}^2, & M_1 > M_2, \\ -\frac{GM_1}{X_{L_2}-X_\omega} - \frac{GM_2}{X_{L_2}-X_\omega+A} - \frac{1}{2}\omega^2 \times X_{L_2}^2, & M_1 < M_2\,, \end{cases} \tag{18}$$

where X_ω is the distance between the primary and the axis through the mass center (Figure 2, $X_\omega = \frac{M_2 A}{(M_1+M_2)}$), X_{L2} is the distance between the outer Lagrangian point L_2 and the axis through the mass center of the system.

5.2 Mass Loss via the Outer Lagrangian Point

The condition for the occurrence of mass loss via the outer Lagrangian point is

$$\begin{array}{ll} \bar{\Psi}_2 \geq \Psi_{L_2}, & \text{when } M_1 > M_2, \\ \bar{\Psi}_1 \geq \Psi_{L_2}, & \text{when } M_1 < M_2. \end{array} \tag{19}$$

There are two ways to calculate the rate of mass loss through the outer Lagrangian point: The first is the theoretical calculation based on the requirement that the average potential of the component changes simultaneously with that of the outer Lagrangian point, but this theoretical calculation is rather complicated. The second is an approximate calculation with the use of an adjustable parameter. We approximate the mass loss rate by,

$$\frac{\Delta M_L}{\Delta t} = \begin{cases} -C_L \frac{M_1+M_2}{2}(\bar{\Psi}_2 - \Psi_{L_2}), & M_1 \geq M_2, \\ -C_L \frac{M_1+M_2}{2}(\bar{\Psi}_1 - \Psi_{L_2}), & M_1 < M_2\,, \end{cases} \tag{20}$$

where the constant C_L is a parameter to be adjusted. The physical condition of Equation (20) is that the mass loss rate is changed by the requirement that the average potentials of the component should be changed simultaneously with that of the outer Lagrangian point. Furthermore, the effect of the total mass of the components on the rate of mass loss is also taken into consideration in this equation.

The following cases can occur when the mass loss rate is calculated with Equation (20): If the chosen value of the parameter C_L is very small, it needs several episodes of mass loss from the outer Lagrangian point before the common envelope loses enough of mass to terminate the process of mass loss. Or, if the chosen value of the parameter C_L is very large, the potential of the component becomes smaller after the mass transfer than that of the outer Lagrangian point, so terminating the process of mass loss via the outer Lagrangian point.

5.3 Angular Momentum Loss via the Outer Lagrangian Point

It is assumed that the components are in synchronous rotation and the mass lost, ΔM_L, was distributed within a shell on the surface of the components before escaping. If the shell is approximated as rigid body, then the angular momentum carried away by ΔM_L can be written as:

$$\Delta J_L = \left(\frac{2}{3}R_1^2 + X_\omega^2\right)\frac{\Delta M_L \times M_1}{M_1 + M_2}\omega + \left(\frac{2}{3}R_2^2 + (A - X_\omega)^2\right)\frac{\Delta M_L \times M_2}{M_1 + M_2}\omega, \tag{21}$$

where X_ω is the distance between the primary and the axis through the mass center of the system and ω is the angular velocity of the binary system. The terms $(\frac{2}{3}R_1^2+X_\omega^2)\frac{\Delta M_L\times M_1}{M_1+M_2}$ and $[\frac{2}{3}R_2^2+(A-X_\omega)^2]\frac{\Delta M_L\times M_2}{M_1+M_2}$ are the moments of inertia of the shells on the surface of the primary and the secondary, and R_1 and R_2 are their radii. The first and second terms on the right side of Equation (21) correspond to the angular momentum carried away by the mass lose from the primary and the secondary, respectively.

6 COMPUTATIONS AND RESULTS

To study the effects of above physical processes on the structure and evolution of the contact binaries, the evolution of a binary system consisting of a $12M_\odot$ and a $5M_\odot$ stars has computed with a modified stellar evolution code for the evolution of rotating binaries (see Huang 2004). The code is updated to include the calculations of mass and energy exchange between the components and the losses of mass and angular momentum via the outer Lagrangian point during the contact phase. Both components in the system are treated simultaneously to include the effects of mass loss due to stellar wind, effect of convective overshooting, the effects of rotation and tide, and the mass transfer between the components. The evolution of the binary system is followed from the zero age main sequence to the later stage after the contact phase. An initial chemical composition of $X = 0.70$ and $Z = 0.02$ is adopted for both stars. The initial orbital separation between the components is taken to be $17.013R_\odot$, so that both stars fill up the Roche lobes during the central hydrogen-burning phase for the primary. Owing to the short timescale of the contact phase, the losses of mass and angular momentum due to stellar wind can be neglected in this phase. In order to show the effects of rotation and tide, two evolutionary sequences one with and one without the effects of rotation and tide were calculated. The sequence, denoted by STD, corresponds to the evolution without effects of rotation and tide, while the sequence denoted by ROT corresponds to that with the effects of rotation and tide. The initial masses of the components and the initial orbital separation between the components, as well as the values of the parameters C and C_L in Equations (13) and (20), are the same for the two sequences. The evolutionary tracks of the primary in the HR diagram for the two sequences are displayed in Figure 3, the solid curve corresponding to STD, the dashed curve, to ROT. Points 'a', 'b', 'c', 'd', 'e', 'f', and 'g' on the tracks represent, in order, the zero age main sequence, the beginning of the Roche lobe overflow, the beginning of the contact phase, the start of the mass loss from the outer Lagrangian point, the end of the central hydrogen-burning phase, and the end of the calculations.

From the difference between the solid and dashed curves in Figure 3 we can find that the effect of rotation and tide cause the evolutionary track of the primary to shift toward a lower luminosity and a lower effective temperature. It shows that the effects of rotation and tide are significant not only during the main sequence stage, but also during the later stages. Table 1 lists the ages, orbital periods, masses, luminosities and effective temperatures of the primary and the secondary, the central hydrogen and helium contents of the primary, and the surface hydrogen content of the primary. From the values at point 'b' and 'c' in Table 1, we see that the Roche lobe mass overflow and the contact phase begin at $t = 1.4597 \times 10^7$ yr and $t = 1.4601 \times 10^7$ yr for the STD sequence, and at $t = 1.4292 \times 10^7$ yr and $t = 1.4447 \times 10^7$ yr for the ROT sequence. Thus, the ROT sequence advances the beginning of the semi-detached and the contact phase by 3.05×10^5 yr and 1.54×10^5 yr. This can be understood by the fact that the components of the ROT sequence are non-symmetric rotational ellipsoids due to the effect of rotation and tide, and the average potentials on the non-symmetric rotational ellipsoids are greater than those on the spherical bodies, and the criterions for the onset of semi-detached phase and contact phase are related to the average potentials of the components in comparison with that of the inner Lagrangian point. Due to the difference between the beginning times of the semi-detached phase, the central hydrogen composition of the primary at point 'b' has a value of $X(c) = 0.2054$ for the STD sequence compared to 0.2606 for the ROT sequence.

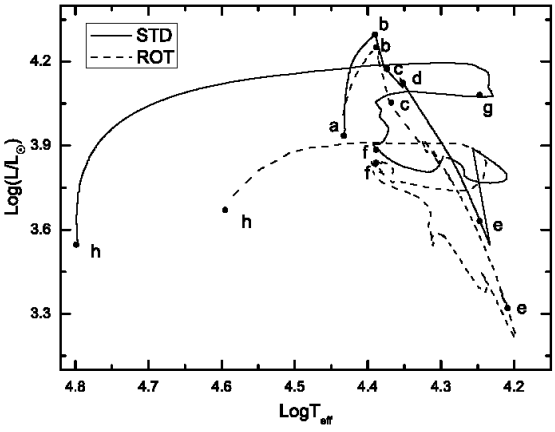

Fig. 3 Evolutionary tracks of the primary in the HR diagram for a binary system consisting of a $12M_\odot$ and a $5M_\odot$ star. The curve labelled STD corresponds to the evolution without the effects of rotation and tide, while the curve labelled ROT corresponds to that with the effects of rotation and tide included.

In Table 1 one can find that the STD sequence reaches point 'f' (end of the central hydrogen-burning phase) at $t = 1.9667 \times 10^7$ yr, while the ROT sequence reaches point 'f' at $t = 2.3105 \times 10^7$ yr. Thus, the ROT sequence is later by about 15% in reaching the point 'f'. This can be understood by the fact that the hydrogen fuel in the central burning kernel of the primary at the beginning of Roche lobe overflow (point 'b') is larger in ROT than in STD.

Figure 4 illustrates the variation of the parameter IOVER with time. The values of IOVER of 1, 2, and 3 in Figure 4 correspond to, respectively, the semi-detached phase ($\bar{\Psi}_1 > \Psi_{L1}$ and $\bar{\Psi}_2 < \Psi_{L1}$), the contact phase ($\bar{\Psi}_1 > \Psi_{L1}$ and $\bar{\Psi}_2 > \Psi_{L1}$), and the phase of mass loss through the outer Lagrangian

Table 1 The parameters at different evolutionary points 'a'–'h' for the STD and ROT sequences. These points have the same meanings as in Figure 3.

Seq	$t(10^7\,\mathrm{yr})$	P (d)	$M_1(M_\odot)$	$M_2(M_\odot)$	$\log L_1/L_\odot$	$\log T_{1\mathrm{eff}}$	$X_1(c)$	$Y_1(c)$	X_1	Y_1	V_{rot} (km s^{-1})
a											
STD	0.0000	1.870	12.000	5.000	3.943	4.433	0.700	0.2800	0.7000	0.2800	
ROT	0.0000	1.870	12.000	5.000	3.943	4.433	0.7000	0.2800	0.7000	0.2800	119.62
b											
STD	1.459756	1.979	11.875	4.999	4.297	4.390	0.2054	0.7746	0.7000	0.2800	
ROT	1.4292167	1.979	11.879	4.999	4.255	4.386	0.2606	0.7194	0.6999	0.2801	193.76
c											
STD	1.460142	1.665	11.354	5.521	4.181	4.378	0.2052	0.7748	0.7000	0.2800	
ROT	1.4447047	1.804	10.660	6.216	4.053	4.371	0.2524	0.7276	0.7000	0.2800	184.19
d											
STD	1.4607206	1.218	9.872	6.984	3.985	4.318	0.2049	0.7751	0.700	0.280	
ROT											
e											
STD	1.4616820	1.225	7.034	9.642	3.547	4.234	0.2046	0.7754	0.700	0.280	
ROT	1.4460107	2.089	6.851	10.025	3.326	4.211	0.2521	0.7279	0.7000	0.2800	140.87
f											
STD	1.966684	2.316	4.287	12.339	3.888	4.387	0.0000	0.9800	0.4854	0.4946	
ROT	2.3105	1.980	4.307	12.569	3.767	4.388	0.0000	0.9800	0.4464	0.5336	109.43
g											
STD	1.967784	10.437	2.116	14.483	4.138	4.234	0.0000	0.9800	0.1748	0.8052	
ROT											
h											
STD	2.0078040	2.000	1.922	14.617	3.542	4.797	0.0000	0.8822	0.1505	0.8295	
ROT	2.33853	7.442	1.713	15.161	3.665	4.595	0.0000	0.9800	0.1505	0.8295	64.30

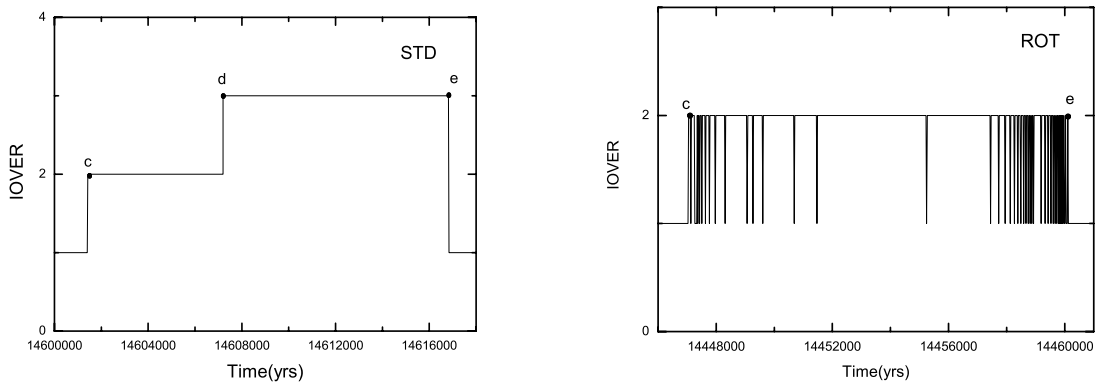

Fig. 4 Variations of the parameter IOVER for the STD and ROT sequences during the contact phase. The values of 1, 2 and 3 of the parameter IOVER correspond to semi-detached phase, contact phase and onset of mass and angular momentum loss via the outer Lagrangian point, respectively.

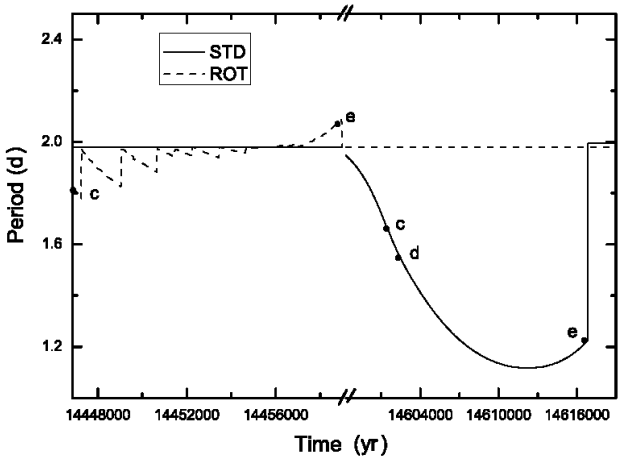

Fig. 5 Variations of the orbital period with time for a contact binary system consisting of a $12M_{\odot}$ and a $5M_{\odot}$ star. The dashed and the solid curves correspond to the cases with and without the effects of rotation and tide, respectively.

point ($\bar{\Psi}_1 > \Psi_{L1}$ and $\bar{\Psi}_2 > \Psi_{L2}$). Figure 4 shows that the parameter IOVER has the values of 2 or 3 during the contact phase (from Point 'c' to 'e') for the STD sequence, while it has the values of 1 or 2 for the ROT sequence during the same period. This implies that the STD sequence remains in the contact phase and undergoes losses of mass and angular momentum through the outer Lagrangian point, while the ROT sequence does not have losses of mass and angular momentum from the outer Lagrangian point and changes into semi-detached system frequently. This means that the effects of rotation and tide can suppress the appearance of mass and angular momentum loss via the outer Lagrangian point, and can cause the state of the system to change between contact and semi-contact phases frequently.

Figure 5 displays the evolution of the orbital period during the contact phase. The solid curve corresponds to the STD sequence, and the dashed curve, the ROT sequence. The figure shows that the contact phase begins earlier in the ROT sequence than in the STD sequence, and that the dashed curve for the ROT sequence is composed of a slowly increasing curve with some short-term variations during the contact phase (from point 'c' to 'e'). This can be understood by the fact that due to the effect of rotation and tide, the system changes frequently to and fro between contact and semi-detached (see Fig. 4), and the orbital

distance between the components (also the period of the system) jumps up and down correspondingly. The phenomena of short variations occurring in a slowly increasing period have been observed in a number of contact systems (Qian et al. 2006a, b). The solid curve (the STD system) in Figure 5 shows that, here, the period decreases with time rapidly. This can be understood by the angular momentum loss via the outer Lagrangian point in this case.

Table 1 shows that for both STD and ROT sequences, during the contact phase (from point 'c' to 'e') the mass of the primary decreases and the mass of the secondary increases. This shows that although mass can flow to and fro between the two components in the common envelope, the net result of the mass transfer process in the contact phase is a transfer of mass from the primary to the secondary. This is an important feature of the contact binary systems, and should be verified observationally.

7 CONCLUSIONS

For a massive contact binary system consisting of a $12M_{\odot}$ and a $5M_{\odot}$ star, the following results were obtained: 1) There exists mass and energy transfer between the components in the common envelope of the contact system. The net result of the mass transfer process is mass transfer from the primary to the secondary during the whole contact phase. 2) A special feature of the contact system is the occurrence of mass and angular momentum loss via the outer Lagrangian point. It can affect the orbital period of the system significantly. However, the occurrence of this process can be affected, even suppressed, by the effect of rotation and tide. 3) The effect of rotation and tide precipitates the beginning of the semi-detached and the contact phases, and delays the end of its hydrogen-burning phase. Furthermore, it can change not only the occurrence of mass and angular momentum loss via the outer Lagrangian point, but also the contact/semi-contact status of the system. Thus, this effect can result in the special phenomenon of some short variations occurring in the slow increase of the period with time. The effect of rotation and tide affects not only the evolution of the main sequence stage, but also that of the later stages.

Acknowledgements The work is supported by the National Nature Science Foundation of China through grant Nos. 10573031 and 10473021.

References

Eggleton P. P., 1983, ApJ, 268, 368
Hazlehrust J., Meyer-Hofmeister E., 1973, A&A, 24, 379
Hazlehrust J., Refsdal S., 1980, A&A, 84, 200
Hazlehrust J., Refsdal S., 1984, A&A, 133, 63
Huang R. Q., 2004, A&A, 422, 981
Huang R. Q., Taam E. R., 1990, A&A, 236, 107
Huang R. Q., Yu K. N., 1998, Stellar Astrophysics, Springer-Verlag
Kähler H., Matraka B., Weigert A., 1986, A&A, 159, 317
Kippenhahn R., Thomas H. C., 1970, In Stellar Rotation, ed. A. Slettebak (Holland: D. Reidel Publ.Co.Dordrecht), 20
Kippenhahn R., Weigert A., 1990, In: Stellar Structure and Evolution, Berlin: Springer Verlag, p.468
Li L., Han Z., Zhang F., 2004a, MNRAS, 351, 137
Li L., Han Z., Zhang F., 2004b, MNRAS, 355, 1388
Li L., Han Z., Zhang F., 2005, MNRAS, 360, L372
Qian S. B., Liu L., Soonthornthum B., Zhu L. B., He J. J., 2006a, AJ, 131, 3028
Qian S. B., Liu L., Kreiner J. M., 2006b, New Astronomy, 12, 117
Maeder A., Meynet G., 2000, ARA&A, 38, 43
Rahunen T., 1981, A&A, 102, 81
Robertson J. A., Eggleton P. P., 1977, MNRAS, 179, 359