FROM DINUCLEAR SYSTEMS TO CLOSE BINARY STARS: APPLICATION TO MASS TRANSFER*

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Applying the microscopic nuclear physics ideas to macroscopic stellar systems, we study the evolution of the compact di-stars in mass asymmetry (transfer) coordinate. Depending on the internal structure of constituent stars, the initial mass asymmetry, total mass, and orbital angular momentum, the close di-star system can either exist in symmetric configuration or fuse into mono-star. The limitations for the formation of stable symmetric binary stars are analyzed. The role of symmetrization of asymmetric binary star in the transformation of potential energy into internal energy of binary star and the release of a large amount of energy is revealed.

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1. Introduction

Of great interest for stellar evolution are compact or close binaries, forming di-star compounds with the average distances between the stars of the same order as the sum of their radii [1, 2]. Measuring the period of revolution and the distance between the stars, the masses of the constituents of the di-star system are determined. This method does not require additional model assumptions and, therefore, it is one of the main methods for determining star masses in astrophysics. The observations of the stages of evolution in close binary stars can provide a verification of our understanding of the inner structure and evolution of stars.

Because mass transfer is an important observable for close binaries, it is meaningful and necessary to study the evolution of the system in the mass asymmetry coordinate $\eta = (M_1 - M_2)/(M_1 + M_2)$, where M_k $(k = 1, 2)$ are

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the stellar masses at fixed total mass $M = M_1 + M_2$ of the system [3]. The mass asymmetry plays an important role as the collective coordinate in the evolution of a dinuclear system consisting of two touching nuclei [4]. Nuclear dynamics, of course, is quite different from the gravitational interactions in di-stars. Nuclear reactions are dominated by short-ranged strong interactions to which minor contributions of long-range (repulsive) Coulomb and centrifugal forces are superimposed. The dinuclear approach is a key tool for the description of fusion (merge) of two heavy nuclei and the decay of dinuclear systems, respectively. In the approaching phase and also after fusion, the interacting nuclei will loose mass by emission of protons, neutrons, and light clusters like alpha-particles. Once a critical distance and mass ratio has been reached, fusion occurs. A highly excited compound nucleus is formed with temperature of the order of one to a few MeV, corresponding to 10^{10} K, cooling down rapidly by ejection of nucleons, nuclear clusters, and electromagnetic radiation. Hence, dinuclear reactions are covering essentially the same spectrum of phenomena as expected or observed for di-stars. Thus, one can try to extend the method and results from the femtoscale of microscopic nuclear physics to macroscopic binary stellar systems.

2. Di-star potential energy

The total potential energy of the di-star system

$$U = U_1 + U_2 + V \tag{1}$$

is given by the sum of the potential energies U_k ($k = 1, 2$) of the two stars and star–star interaction potential V. The radiation energy is neglected because the absolute values of the gravitational energy and the intrinsic kinetic energy are much larger than the radiation energy. The energy of the star "k" is

$$U_k = -\omega_k \frac{GM_k^2}{2R_k}\,, \tag{2}$$

where G, M_k, and R_k are the gravitational constant, mass, and radius of the star, respectively. The dimensionless structural factor ω_k is determined by the density profile of the star. Employing the values of the structural factor $\omega_k = 1.644\left(\frac{M_\odot}{M_k}\right)^{1/4}$ and radius $R_k = R_\odot\left(\frac{M_k}{M_\odot}\right)^{2/3}$ of the star from the model of Ref. [2], we obtain

$$\begin{aligned} U_k &= -\omega_0 \frac{GM_k^{13/12}}{2}\,, \\ \omega_0 &= 1.644 \frac{M_\odot^{11/12}}{R_\odot}\,, \end{aligned} \tag{3}$$

where, $M_\odot$ and $R_\odot$ are mass and radius of the Sun, respectively. Note that the model of Ref. [2] well describes the observable temperature–radius–mass–luminosity relations, the spectra of seismic oscillations of the Sun, distribution of stars on their masses, magnetic fields of stars, and *etc.* Since the two stars rotate with respect to each other around the common center of mass, the star–star interaction potential contains, together with the gravitational energy Q of the interaction of two stars, the kinetic energy of orbital rotation $V_{\rm rot}$

$$V(R) = Q + V_{\rm rot} = -\frac{GM_1M_2}{R} + \frac{\mu v^2}{2}\,, \tag{4}$$

where $v = (GM[2/R - 1/R_{\rm m}])^{1/2}$, $\mu = M_1M_2/M$, and $R_{\rm m}$ are the speed, the reduced mass, and the semimajor axis of the elliptical relative orbit, respectively [1]. Finally, one can derive the simple expression for the star–star interaction potential

$$V = -\frac{GM_1M_2}{2R_{\rm m}} = -\omega_V\frac{G(M_1M_2)^3}{2}\,, \tag{5}$$

where $\omega_V = (M^2\mu_{\rm i}^2R_{\rm m,i})^{-1}$. Here, the Kepler's laws $R_{\rm m} = \left(\frac{\mu_{\rm i}}{\mu}\right)^2 R_{\rm m,i}$ ($L = L_{\rm i}$) is used. The index "i" denotes the value of reduced mass of the initial binary star and distance between stars (orbital angular momentum) of the initial binary at $\eta = \eta_{\rm i}$. The final expression for the total potential energy (1) of the di-star system is

$$U = -\frac{G}{2}\left(\omega_0\left[M_1^{13/12} + M_2^{13/12}\right] + \omega_V[M_1M_2]^3\right)\,. \tag{6}$$

Using the mass asymmetry coordinate η instead of masses $M_1 = \frac{M}{2}(1+\eta)$ and $M_2 = \frac{M}{2}(1-\eta)$, we rewrite Eq. (6)

$$U = -\frac{GM_\odot^2}{2R_\odot}\left(\alpha\left[(1+\eta)^{13/12} + (1-\eta)^{13/12}\right] + \beta\left[1-\eta^2\right]^3\right)\,, \tag{7}$$

where

$$\alpha = 1.644\left(\frac{M}{2M_\odot}\right)^{13/12}$$

and

$$\beta = \frac{GM_\odot^5}{2L_{\rm i}^2}\left(\frac{M}{2M_\odot}\right)^5\,.$$

As can be seen from Eq. (7), the stability of the binary star system depends on the orbital angular momentum $L_{\rm i} = \mu_{\rm i}(GMR_{\rm m,i})^{1/2}$ and the total mass M.

Employing Eq. (7), we can study the evolution of the di-star system in the mass asymmetry coordinate η. The extremal points of the potential energy as a function of η are found by solving numerically the equation

$$\frac{\partial U}{\partial \eta} = -\frac{GM_\odot^2}{2R_\odot}\left(\frac{13}{12}\alpha\left[(1+\eta)^{1/12}-(1-\eta)^{1/12}\right]-6\beta\eta\left[1-\eta^2\right]^2\right). \tag{8}$$

As seen, Eq. (8) is solved for $\eta = \eta_{\rm m} = 0$. At this value the potential has an extremum which is a minimum if

$$\alpha < \frac{432}{13}\beta$$

or

$$L_{\rm i} < \left[10.1GR_\odot M_\odot^3\right]^{1/2}\left(\frac{M}{2M_\odot}\right)^{47/24}$$

and a maximum if

$$\alpha > \frac{432}{13}\beta\,.$$

The transition point is

$$\alpha_{\rm cr} = \alpha = \frac{432}{13}\beta = \frac{216}{13}\frac{GM_\odot^5}{L_{\rm i}^2}\left(\frac{M}{2M_\odot}\right)^5.$$

At $\alpha < \alpha_{\rm cr}$, a minimum at $\eta = \eta_{\rm m} = 0$ is engulfed symmetrically by two barriers at $\eta = \pm\eta_{\rm b}$. The fusion of two stars with $|\eta_{\rm i}| < \eta_{\rm b}$ can occur only by overcoming the barrier at $\eta = +\eta_{\rm b}$ or $\eta = -\eta_{\rm b}$. With decreasing ratio α/β, $B_\eta = U(\eta_{\rm b}) - U(\eta_{\rm i})$ increases (Fig. 1 (a)) and the symmetric di-star system becomes more stable. The evolution of two stars with $|\eta_{\rm i}| \neq 0$ and $|\eta_{\rm i}| < \eta_{\rm b}$ to the symmetric di-star configuration is energetically favorable. Hence, an initially asymmetric binary system ($|\eta| = |\eta_{\rm i}| < \eta_{\rm b}$) is driven to mass symmetry, implying a flow of mass towards equilibrium and increase of the internal energy of stars by the amount $\Delta U = U(\eta_{\rm i}) - U(\eta = 0)$ (Fig. 1 (a)). At $\alpha \geq \alpha_{\rm cr}$, $\eta_{\rm m} = \eta_{\rm b} = 0$ and we have the inverse U-type potential with maximum at $\eta = 0$. In such a system, the fusion of stars (one star "swallows" the other star) is the only mode of evolution in η transforming in the end the di-star into a mono-star with the release of energy $E_{\rm f} = U(\eta_{\rm i}) - U(\eta = 1)$ (Fig. 1 (b)).

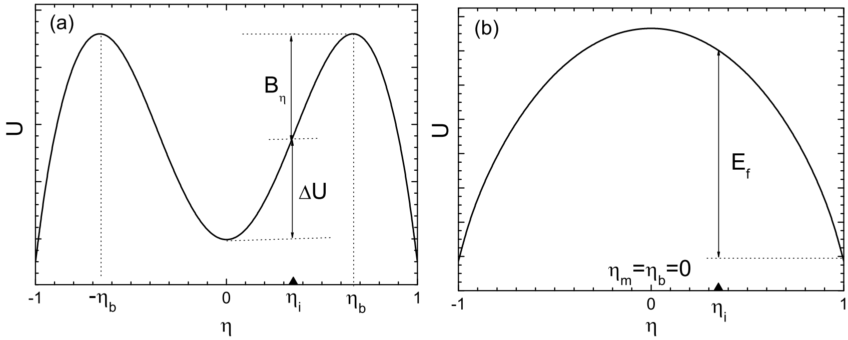

Fig. 1. The schematical drawings of the driving potential energy of the star–star system at $\alpha < \alpha_{\rm cr}$ (a), and $\alpha > \alpha_{\rm cr}$ (b). The arrows on x-axis show the corresponding initial binary stars. The notations used in the text are indicated.

3. Calculated results

In the calculations, we assume the conservative evolution of the di-star in mass asymmetry coordinate η. The orbital angular momentum $L_{\rm i}$ is calculated by using the experimental masses of stars and the period $P_{\rm orb,i}$ of orbital rotation of the di-star system at $\eta = \eta_{\rm i}$. Various di-stars have different M and $L_{\rm i}$ and, correspondingly, the potential energy shapes. The potential energies (driving potentials) $U(\eta)$ of the close di-star systems *versus* η are presented in Figs. 2, 3, and 4. For all systems considered, $\alpha < \alpha_{\rm cr}$, respectively the potential energies have symmetric barriers at $\eta = \pm\eta_{\rm b}$ and the minimum at $\eta = \eta_{\rm m} = 0$. As seen in Fig. 2, the barrier in η appears as a result of the interplay between the total gravitational energy $U_1 + U_2$ of the stars and the star–star interaction potential V. Both energies have different behavior as a function of mass asymmetry: $U_1 + U_2$ decreases and V increases with changing η from $\eta = 0$ to $\eta = \pm 1$. One should stress that the driving potentials $U(\eta)$ for the di-star systems look like the driving potentials for the microscopic dinuclear systems [4].

The evolution of the di-star system depends on the initial mass asymmetry $\eta = \eta_{\rm i}$ at its formation. If the original di-star is asymmetric, but $|\eta_{\rm i}| < \eta_{\rm b}$, then it is energetically favorable to evolve in η to a configuration in the global minimum at $\eta = 0$, that is, to form a symmetric di-star system. The matter of a heavy star can move to an adjacent light star enforcing the symmetrization of di-star without additional driving energy. The symmetrization of asymmetric binary star leads to the decrease of potential energy U or the transformation of the potential energy into internal energy of stars. The resulting symmetric di-star is created at large excitation energy. For example, for the binary systems RR Cen ($\eta_{\rm i} = 0.65$), V402 Aur

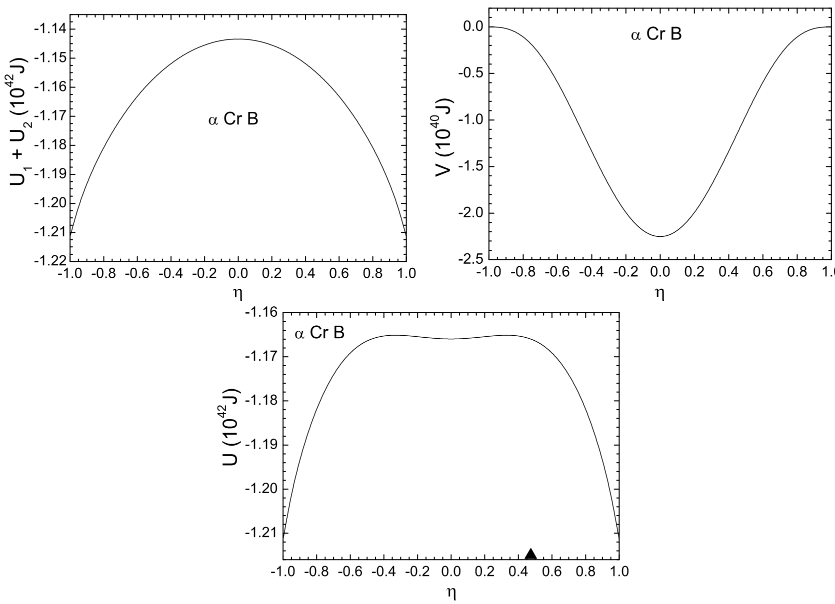

Fig. 2. The calculated gravitational energy $U_1 + U_2$, star–star interaction energy, and total potential energy U *versus* η for close binary star α Cr B. The arrows on x-axis show the initial $\eta_{\rm i}$.

($\eta_{\rm i} = 0.66$), and V921 Her ($\eta_{\rm i} = 0.61$), the internal energies of stars increase during symmetrization by amount $\Delta U = U(\eta_{\rm i}) - U(\eta = 0) = 2\times 10^{41}$, 10^{41}, and 10^{41} J, respectively. As the most of close binary stars are asymmetric ones, the symmetrization process leads to the release of a large amount of energy in these systems and can be an important source of energy in the universe (Table I). Note that accounting for the loss of angular momentum will lead to an increase of the value ΔU.

If $|\eta_{\rm i}| > \eta_{\rm b}$ or $\eta_{\rm b} = 0$, the di-star system is unstable and evolves towards the mono-star system, thus, enforcing the asymmetrization of the di-star. The matter is transferred from the light star to the heavy star even without additional external energy. We found only one close binary system α Cr B ($M_1 = 2.58 M_\odot$, $M_2 = 0.92 M_\odot$, $\omega_1 = 1.30$, $\omega_2 = 1.68$, $\beta/\alpha = 0.039$) for which $|\eta_{\rm i}| = 0.47 > \eta_{\rm b} = 0.33$ (Fig. 2).

Since the fusion barriers B_η in η are quite large for the systems with $|\eta_{\rm i}| < \eta_{\rm b}$ in Table I, the formation of a mono-star from the di-star system by the thermal diffusion in mass asymmetry coordinate is strongly suppressed. Perhaps, the existence of barrier in η is the reason why very asymmetric close double-stars systems with $|\eta_{\rm i}| > \eta_{\rm b}$ are rarely observed. This imposes restrictions on the asymmetric configurations with $|\eta| > \eta_{\rm b}$ of the di-star systems.

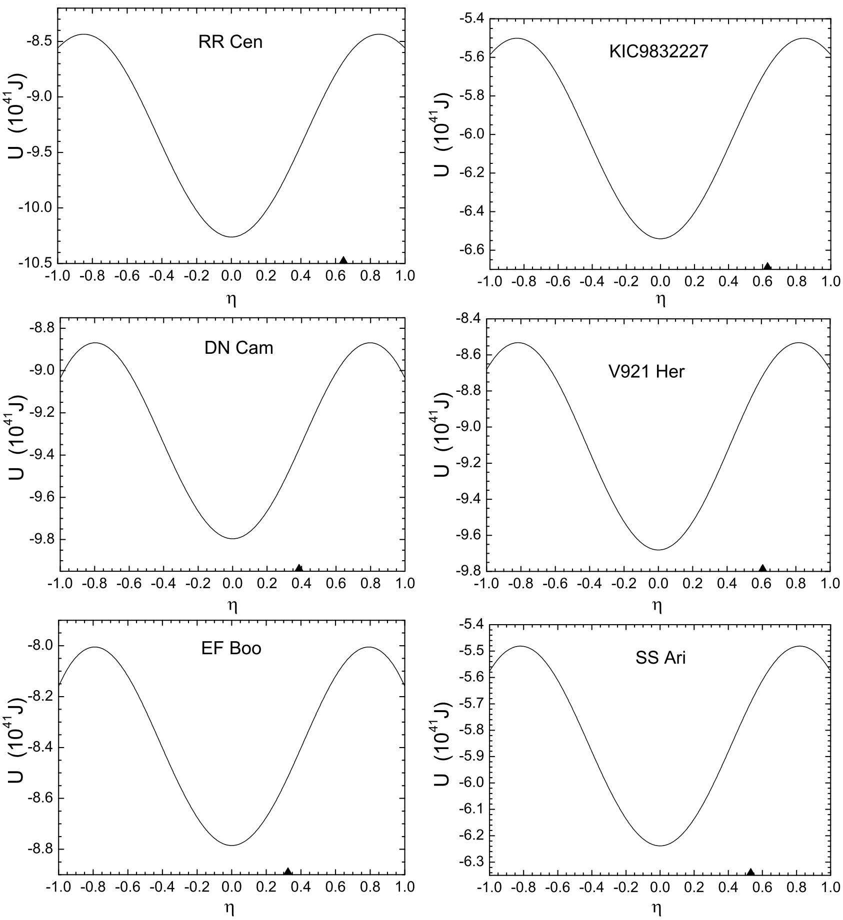

Fig. 3. The calculated total potential energies U *versus* η for the indicated close binary stars. The arrows on x-axis show the corresponding initial $\eta_{\rm i}$ for binary stars.

The value of α becomes larger than $\alpha_{\rm cr}$ and the minimum in $U(\eta)$ disappears, and di-star asymmetrization (fusion in η coordinate) occurs as the result of a release of matter from one of the stars or an increase of orbital momentum due to the strong external perturbation, *i.e.* by the third object, or the spin–orbital coupling in the di-star.

A spectacular recent case is KIC 9832227 which was predicted [5] to be merged in 2022, enlightening the sky as a red nova. For the fate of KIC 9832227 ($\eta_{\rm i} = 0.63$, $\eta_{\rm b} = 0.84$), we predict that a fast merger is excluded (Fig. 3). This di-star is driven instead towards the mass symmetry. The mass is transferring from heavy star to light one and the relative distance between two stars and the period of the orbital rotation are decreasing.

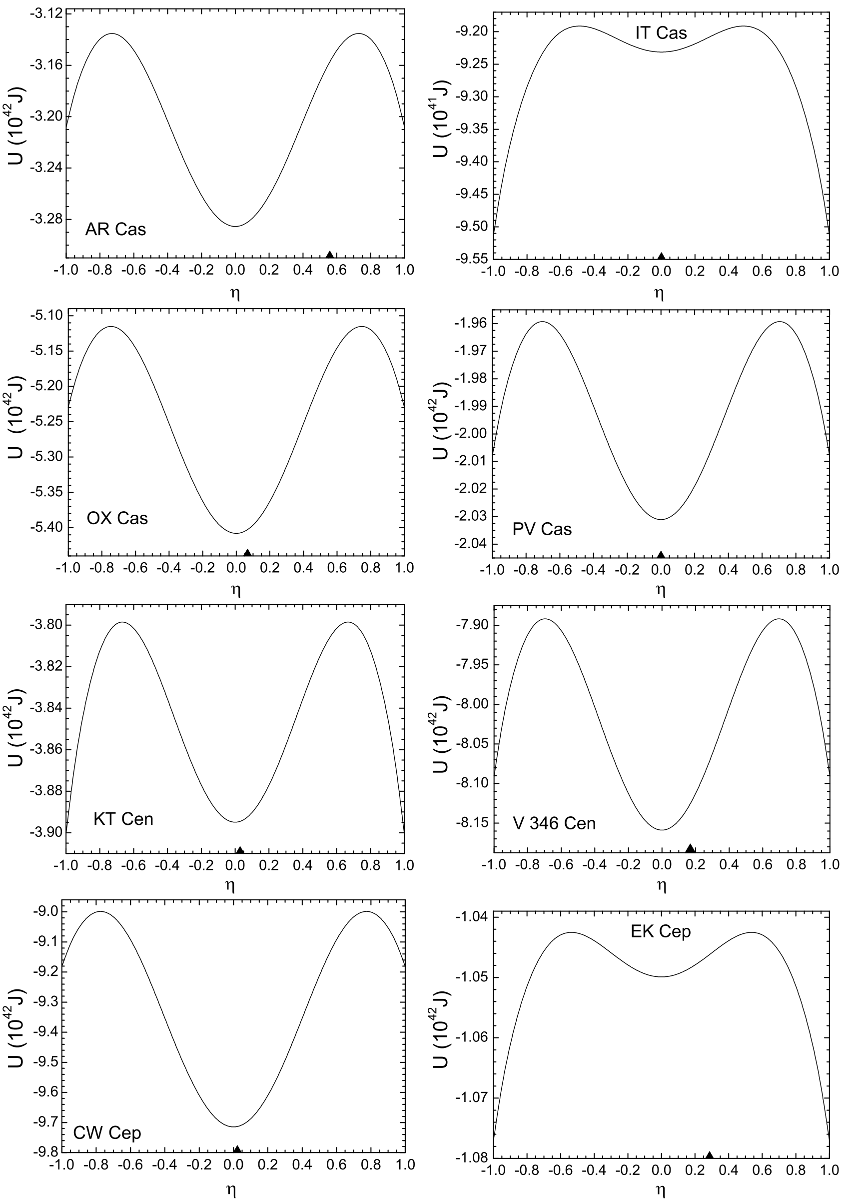

Fig. 4. The same as in Fig. 3, but for the indicated close binary stars. The observed data are from Ref. [2].

A huge amount of energy $\Delta U \approx 10^{41}$ J is released during the symmetrization. As seen in Fig. 3, the di-stars KIC 9832227 and RR Cen ($\eta_{\rm i} = 0.65$, $\eta_{\rm b} = 0.85$) have almost the same $\eta_{\rm i}$, $\eta_{\rm b}$, and potential energy shapes. So, the observation of the RR Cen di-star is also desirable. It should be stressed that the observational data of Ref. [7] negate the 2022 red nova merger prediction [5].

TABLE I

The calculated ω_1, ω_2, β/α, $\Delta U = U(\eta_{\rm i}) - U(\eta = 0)$, $B_\eta = U(\eta_{\rm b}) - U(\eta_{\rm i})$, and observed data $M_1/M_\odot$, $M_2/M_\odot$ [6] for the contact binary stars indicated.

Di-star	$\frac{M_1}{M_\odot}$	$\frac{M_2}{M_\odot}$	ω_1	ω_2	β/α	ΔU (J)	B_η (J)
AB And	1.01	0.49	1.64	1.96	0.261	2×10^{40}	3×10^{40}
GZ And	1.12	0.59	1.60	1.88	0.283	2×10^{40}	4×10^{40}
OO Aql	1.05	0.88	1.62	1.70	0.180	10^{39}	3×10^{40}
V417 Aql	1.40	0.50	1.51	1.96	0.359	5×10^{40}	3×10^{40}
SS Ari	1.31	0.40	1.54	2.07	0.372	6×10^{40}	2×10^{40}
V402 Aur	1.64	0.33	1.45	2.17	0.512	10^{41}	10^{40}
TY Boo	0.93	0.40	1.67	2.07	0.275	2×10^{40}	2×10^{40}
EF Boo	1.61	0.82	1.46	1.73	0.282	3×10^{40}	5×10^{40}
AO Cam	1.12	0.49	1.60	1.97	0.295	3×10^{40}	3×10^{40}
DN Cam	1.85	0.82	1.41	1.73	0.298	4×10^{40}	5×10^{40}
TX Cnc	0.91	0.50	1.68	1.96	0.212	9×10^{39}	2×10^{40}
RR Cen	2.09	0.45	1.37	2.01	0.542	2×10^{41}	2×10^{40}
V752 Cen	1.30	0.40	1.54	2.07	0.391	6×10^{40}	2×10^{40}
V757 Cen	0.88	0.59	1.70	1.88	0.212	5×10^{39}	3×10^{40}
VW Cep	0.93	0.40	1.67	2.07	0.300	2×10^{40}	2×10^{40}
TW Cet	1.06	0.61	1.62	1.86	0.258	10^{40}	4×10^{40}
RW Com	0.56	0.20	1.90	2.46	0.283	10^{40}	8×10^{39}
RZ Com	1.23	0.55	1.56	1.91	0.303	3×10^{40}	3×10^{40}
V921 Her	2.07	0.51	1.37	1.95	0.364	10^{41}	2×10^{40}

4. Conclusions

The isolated close binary star systems evolve along well-defined trajectories in classical phase space. We have shown that energy conservation is enough to fix the trajectory of the system in the potential energy landscape defined by the total mass and orbital angular momentum of system. Exploiting the stationarity of the total energy, stability conditions were derived and investigated as functions of the mass asymmetry parameter η. We have shown that this collective degree of freedom plays a comparable important role in macroscopic object as well as in microscopic dinuclear systems. In close di-star systems, the mass asymmetry coordinate can govern the fusion and symmetrization processes of two stars. An interesting aspect is that once η has been determined *e.g.* by observation, it allows to conclude on the stellar structure parameters.

For all systems considered, $\alpha < \alpha_{\rm cr}$ and the potential energies have symmetric barriers at $\eta = \pm\eta_{\rm b}$ and the minimum at $\eta = \eta_{\rm m} = 0$. At $\alpha < \alpha_{\rm cr}$, two distinct evolution scenario arise. Let the di-star system be initially formed with $\eta = \eta_{\rm i}$. The two stars start to exchange matter where the fate of the binary depends critically on the mass ratio: If $|\eta_{\rm i}| < \eta_{\rm b}$, the system is driven to the symmetric di-star configuration (towards a global minimum of the potential landscape). However, if $|\eta_{\rm i}| > \eta_{\rm b}$, the system evolves towards the mono-star system. All asymmetric close binary stars considered, except α Cr B, satisfy the condition $|\eta_{\rm i}| < \eta_{\rm b}$ and in these systems the symmetrization process occurs. Note that for many systems $U(\eta = 0) < U(|\eta| = 1)$.

In the case of $|\eta_{\rm i}| < \eta_{\rm b}$ ($\alpha < \alpha_{\rm cr}$), the symmetrization of stars leads to the release of a large amount of energy ($\sim 10^{40-41}$ J). Thus, the symmetrization of stars in close binary systems is one of the important sources of the transformation of the gravitational energy to other types of energy in the universe.

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