From a Dinuclear System to Close Binary Cosmic Objects

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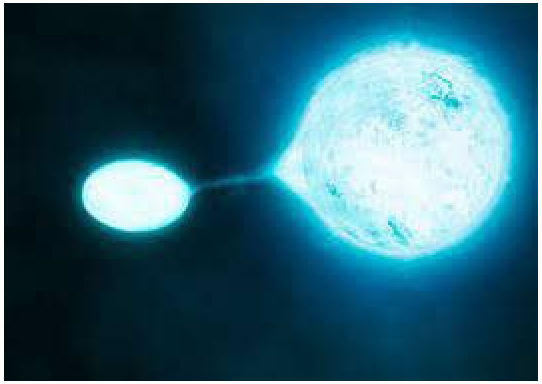
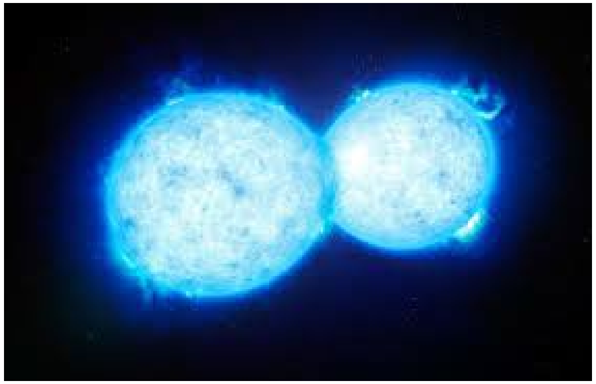
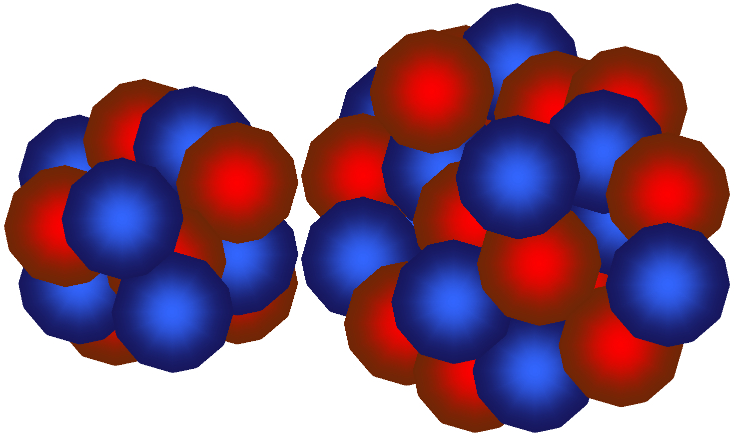
-Di-star systems are widespread objects: about a quarter of all stars belong to the di-star family. Compact or close di-stars (binaries) with separation distances of only a few stellar diameters are of interest for stellar evolution, for example, for a merger process of stars.







Dinuclear system

-The distinctive feature of close binary systems is matter transfer. Merging contact binary stars lead to luminous red novae.

-The Darwin instability occurs when the mass ratio becomes small enough, and the heavy star can no longer keep the light star synchronously rotating via tidal interaction. The orbital angular momentum transferred from the intrinsic spin changes the orbit more than the spin, which leads to a runaway. As found, for massive primary stars of the main sequence, this happens at a mass ratio of 0.09.

-There is also another scenario: after contact of stars, there is a brief but intense mass transfer in a di-star system, changing the originally more massive star into a less massive one. This process may oscillate until a stable contact configuration is eventually achieved. A dynamic mass transfer without the Darwin instability was also investigated, and mergers triggered by a tidal runaway based on a non-equilibrium response to tidal dissipation were considered.

- The problem of the origin of binary stars or binary galaxies is still unclear. There is no dissociative equilibrium between single and binary stars in the galaxy. The number of binary stars is many orders of magnitude larger than expected for dissociative equilibrium. So the origin of binary stars is not related to the capture of one star by another into a bound orbit. In addition, there is no sharp difference between close and wide binary stars, and the angular momenta relative to their centers of gravity are extremely large.

Theoretical Approach

$\eta = (M_1 - M_2)/(M_1 + M_2)$, where M_i $(i = 1, 2)$ are the masses of the components

$$M = M_1 + M_2$$

Total energy of binary system

$$E = \frac{p_r^2}{2\mu} + U,$$

$$\mu = \mu(\eta) = M_1 M_2/M = M(1-\eta^2)/4$$

Total potential energy

$$U = U_1 + U_2 + V,$$

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

ω_k - the dimensionless structural factor

$$R_k = \frac{1}{g} M_k^n$$

where n and g are the constants. So

$$U_k = -\frac{Gg\omega_k M_k^{2-n}}{2}.$$

Since two objects rotate around the common center of mass, the star–star interaction potential contains, together with the gravitational energy of interaction V_G, the kinetic energy of orbital rotation V_R:

$$V(r) = V_G + V_R = V_G + \frac{L^2}{2\mu r^2},$$

where L is the orbital angular momentum of the binary system, which is conserved during the conservative mass transfer. At $r \geq r_t = R_1 + R_2$ and $r \leq r_t$,

$$V_G(r) = -\frac{GM_1M_2}{r} \qquad \text{and} \qquad V_G(r) = -\frac{GM_1M_2}{2r_t}\left[3 - \frac{r^2}{r_t^2}\right]$$

From the conditions $\partial V/\partial r|_{r=r_m} = 0$ and $\partial^2 V/\partial r^2|_{r=r_m} > 0$

$$r_m = \frac{L^2}{G\mu^2 M} \quad \text{at } r_m \geq r_t \qquad r_m = \left(\frac{L^2 r_t^3}{G\mu^2 M}\right)^{1/4} \quad \text{at } r_m < r_t$$

$$V(r_m) = -\frac{GM_1M_2}{2r_m} = -\frac{G}{2}\omega_V M_1^3 M_2^3$$

at $r_m \geq r_t$ or

$$V(r_m) = -\frac{GM_1M_2}{2r_t}\left[3 - \frac{2r_m^2}{r_t^2}\right] = -\frac{G}{2}\frac{gM_1M_2}{M_1^n + M_2^n}\left[3 - \frac{2g^2}{\omega_V^2 M_1^4 M_2^4 (M_1^n + M_2^n)^2}\right]$$

at $r_m < r_t$. Here,

$$\omega_V = \frac{1}{M^2\mu_i^2 r_{mi}}$$

and r_{mi} and $\mu_i = \mu(\eta_i) = \frac{M_{1i}M_{2i}}{M} = \frac{M}{4}(1 - \eta_i^2)$ are, respectively, the distance between its components and the reduced mass of the initial binary system.

$$r_m = \left(\frac{\mu_i}{\mu}\right)^2 r_{mi}$$

$$U = -\frac{G}{2}\left(g[\omega_1 M_1^{2-n} + \omega_2 M_2^{2-n}] + \omega_V M_1^3 M_2^3\right)$$

at $r_m \geq r_t$ and

$$U = -\frac{G}{2}g\left(\omega_1 M_1^{2-n} + \omega_2 M_2^{2-n} + \frac{M_1 M_2}{M_1^n + M_2^n}\left[3 - \frac{2g^2}{\omega_V^2 M_1^4 M_2^4 (M_1^n + M_2^n)^2}\right]\right)$$

at $r_m < r_t$.

Binary Stars

In order to calculate the factor ω_k, we make use of the single-star model from

Vasiliev, B.V. Astrophysics and Astronomical Measurement Data. Available online: http://astro07.narod.ru (accessed on 1 January 2022).

$$\omega_k = 1.644 \left(\frac{M_\odot}{M_k} \right)^{1/4}$$

$$R_k = \frac{1}{g} M_k^{2/3} = R_\odot \left(\frac{M_k}{M_\odot} \right)^{2/3}, \qquad n = 2/3$$

$$U = -\frac{GM_\odot^2}{2R_\odot} \left(\alpha[(1+\eta)^{13/12} + (1-\eta)^{13/12}] + \beta[1-\eta^2]^3 \right) \qquad \text{at } r_m \geq r_t$$

$$U = -\frac{GM_\odot^2}{2R_\odot} \left(\alpha[(1+\eta)^{13/12} + (1-\eta)^{13/12}] \right. \qquad \text{at } r_m < r_t.$$

$$\left. + \beta_1 \frac{1-\eta^2}{(1+\eta)^{2/3} + (1-\eta)^{2/3}} \left[3 - \frac{\gamma}{[1-\eta^2][(1+\eta)^{2/3} + (1-\eta)^{2/3}]^{1/2}} \right] \right)$$

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

$$\beta = \frac{GM^5R_\odot}{64L_i^2M_\odot^2} = \frac{GM_\odot^3R_\odot}{2L_i^2}\left(\frac{M}{2M_\odot}\right)^5,$$

$$\beta_1 = \left(\frac{M}{2M_\odot}\right)^{4/3},$$

$$\gamma = \frac{2^{10/3}L_iM_\odot^{1/3}}{(GR_\odot M^{11/3})^{1/2}}.$$

$$L_i = \mu_i(GMr_{mi})^{1/2} = \mu_i\left(G^2M^2P_{\mathrm{orb},i}/(2\pi)\right)^{1/3}$$

at $\eta = 0$ the potential has a minimum if

$$\alpha < \alpha_{cr} = \frac{432}{13}\beta$$

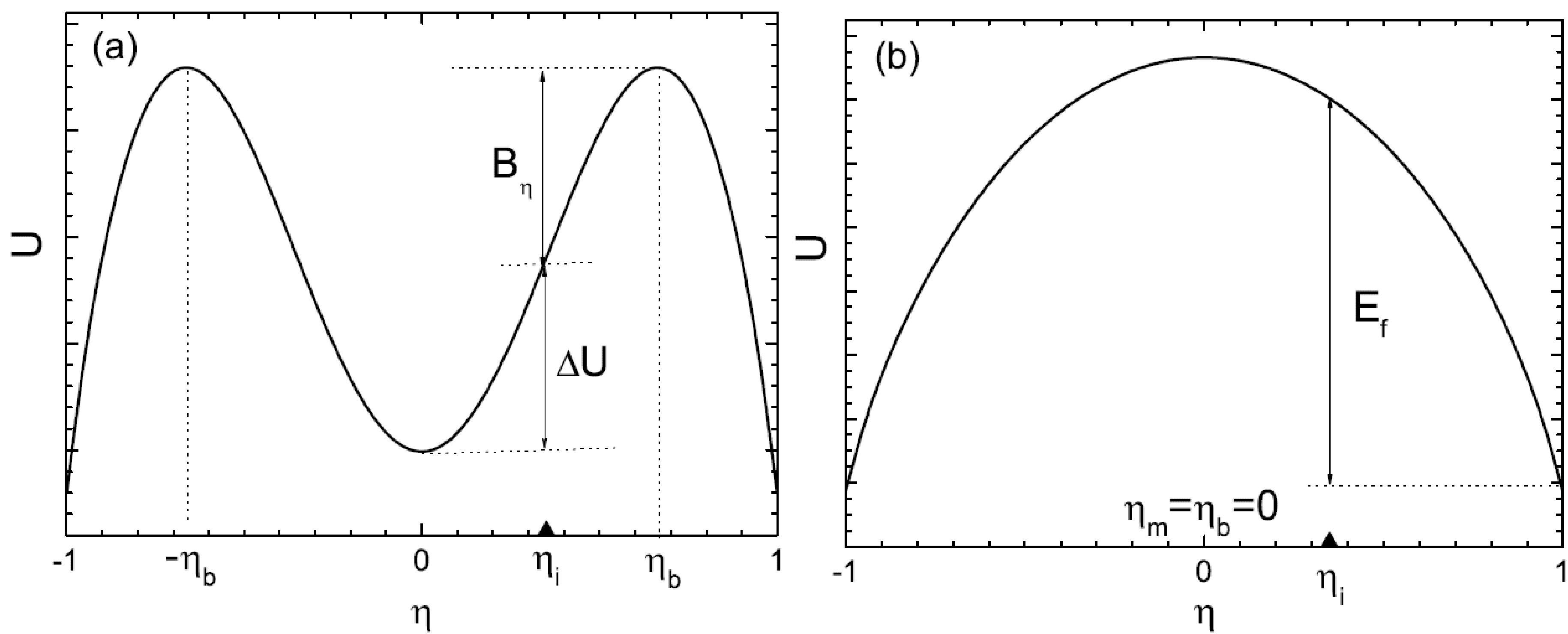
or

$$P_{\mathrm{orb},i} < \frac{128.5\pi}{(1-\eta_i^2)^3}\left(\frac{R_\odot^3}{GM_\odot}\right)^{1/2}\left(\frac{M}{2M_\odot}\right)^{7/8}$$

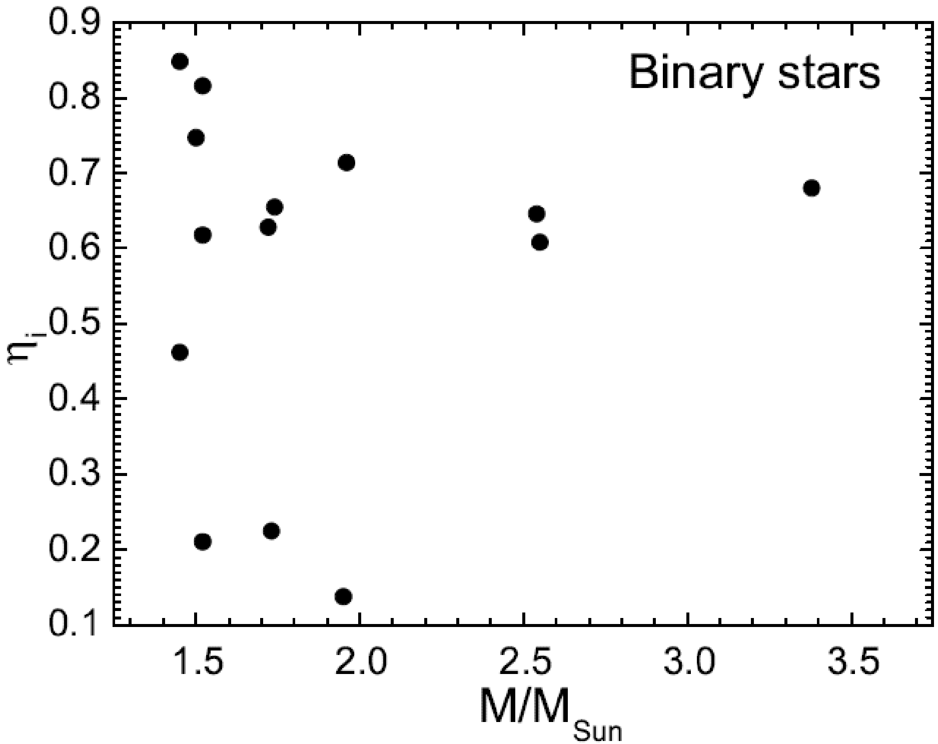
and a maximum if $\alpha > \alpha_{cr}$.

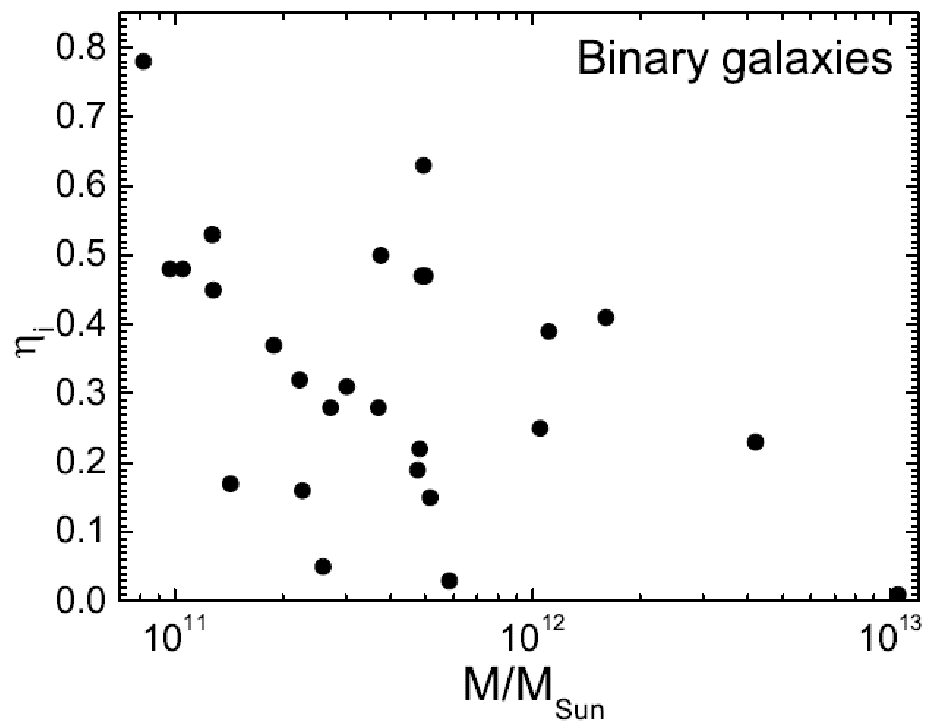
$$\eta_b = 2^{-1/2}\left(\frac{864^2\beta - 22464\alpha}{864^2\beta + 3289\alpha}\right)^{1/2}$$

So at $\alpha < \alpha_{cr}$ the potential energy as a function of η has two symmetric maxima at $\eta = \pm\eta_b$ and the minimum at $\eta = \eta_m = 0$. The fusion of two stars with $|\eta_i| < \eta_b$ occurs only by overcoming the barrier at $\eta = +\eta_b$ or $\eta = -\eta_b$. With decreasing ratio α/β, the value of $B_\eta = U(\eta_b) - U(\eta_i)$ increases and the symmetric di-star system becomes more stable.



$$\Delta U = U(\eta_i) - U(\eta = 0) \qquad E_f = U(\eta_i) - U(\eta = 1)$$





If $\beta \gg \frac{1}{66}\alpha$, then $\eta_b \to 2^{-1/2} \approx 0.71$.

Indeed, close binary stars with a high mass ratio are very rare objects

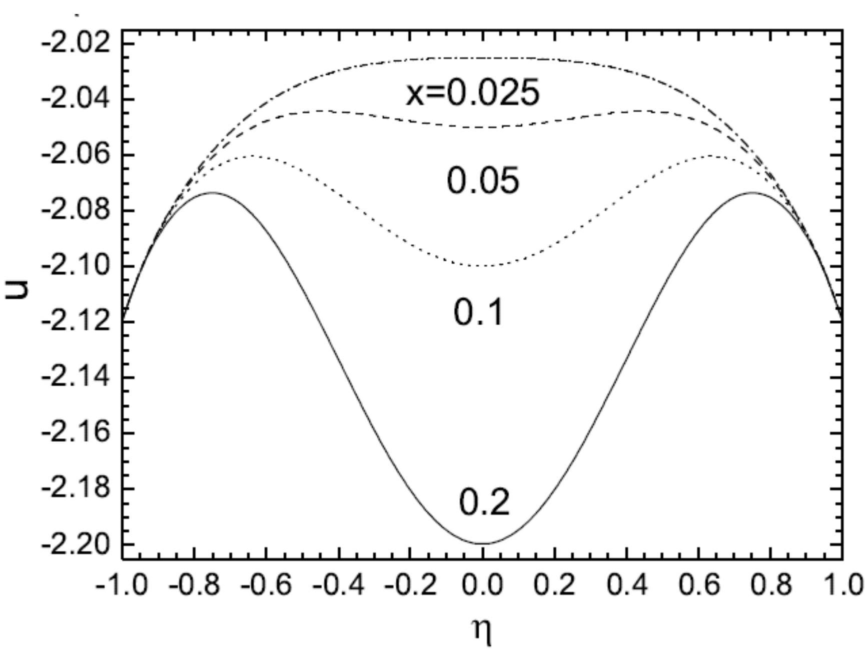
Mass Transfer in Close Binary Cosmic Systems as a Source of Energy in the Universe

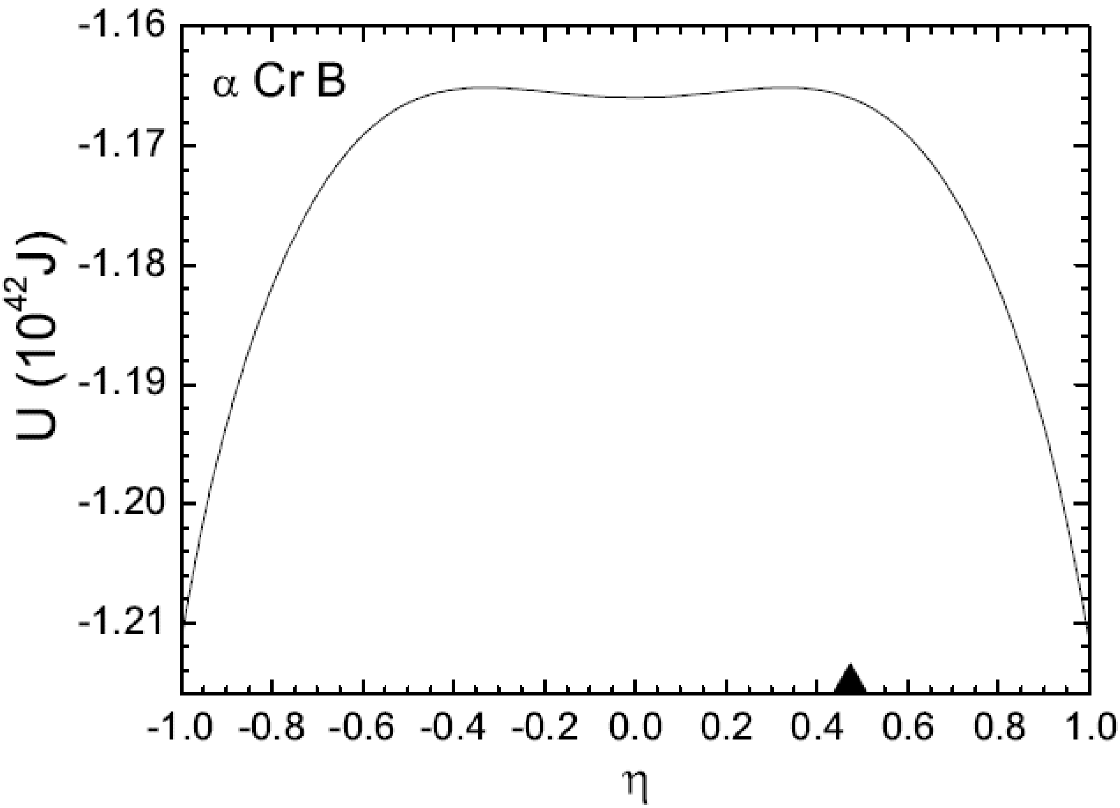
As assumed, the values of L_i and M are conserved during the binary star evolution in η. The orbital angular momentum L_i is found using the observed star masses $M_{1i,2i}$ and period $P_{orb,i}$ of orbital rotation at $\eta = \eta_i$. The binary stars differ in values of M and L_i and, accordingly, have potential energies of a different kind.

One can express the potential energy in units of

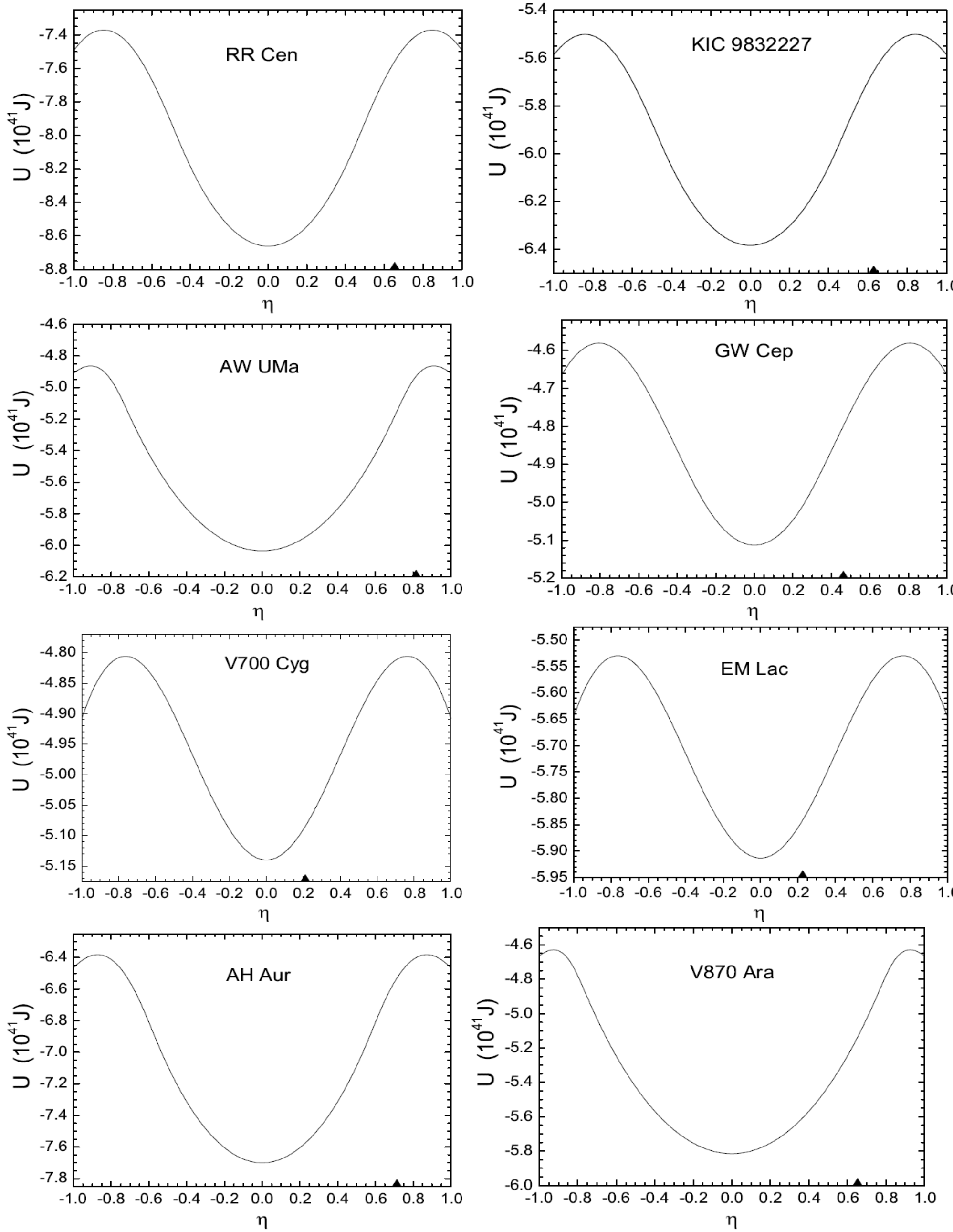
$$u = u_1 + u_2 + xv = (1+\eta)^{13/12} + (1-\eta)^{13/12} + x(1-\eta^2)^3,$$

where $x = \frac{GM_\odot^3 R_\odot}{3.288 L_i^2}\left(\frac{M}{2M_\odot}\right)^{47/12}$

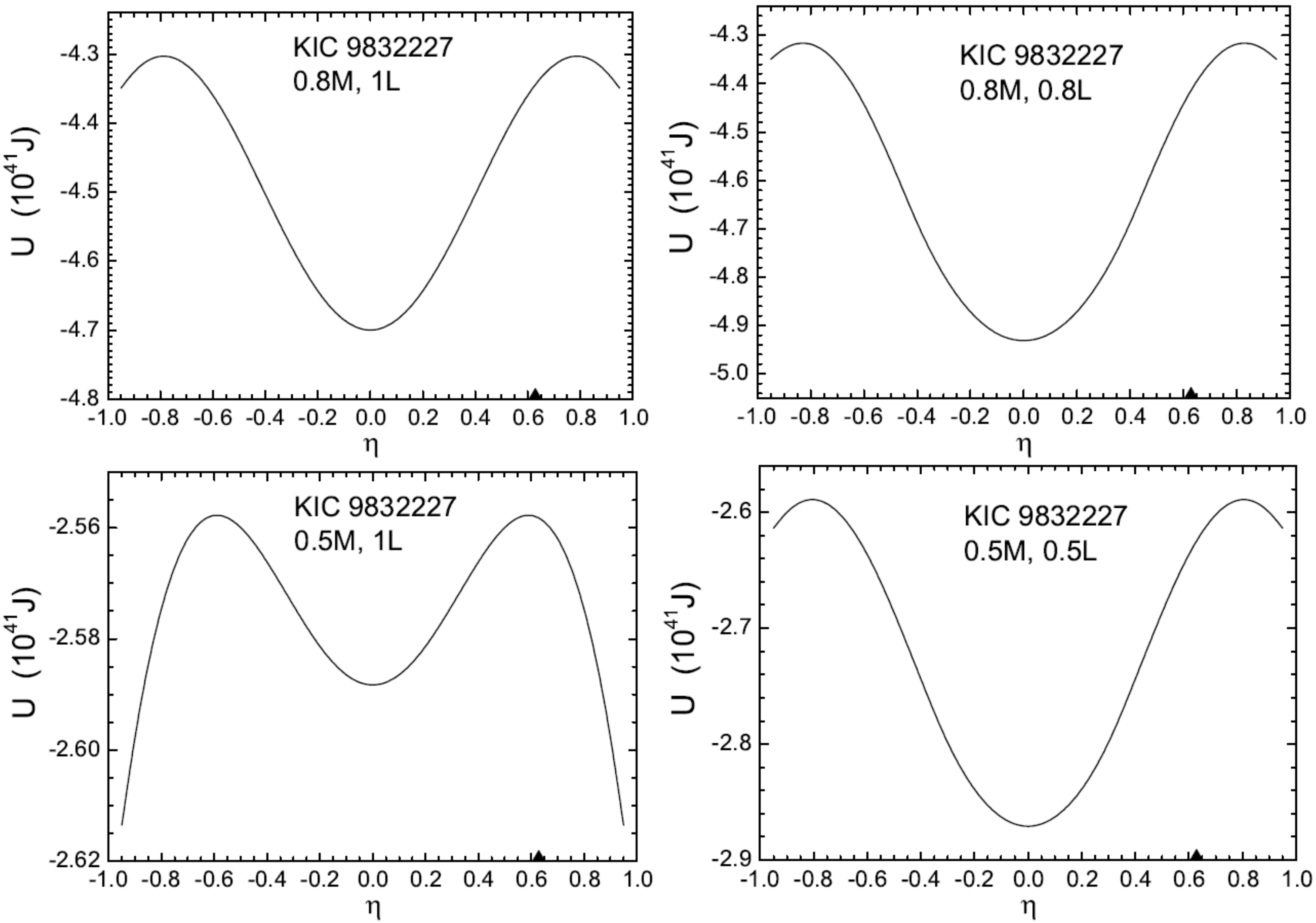




If $|\eta_i| > \eta_b$ or $\eta_b = 0$, the di-star system is unstable with respect to the asymmetrization. The matter is transferred from the light star to the heavy one even without additional external energy. We only know one close binary system α Cr B ($M_1 = 2.58 M_\odot$, $M_2 = 0.92 M_\odot$, $\omega_1 = 1.30$, $\omega_2 = 1.68$, $\beta/\alpha = 0.039$), for which $|\eta_i| = 0.47 > \eta_b = 0.33$ (Figure 4).



A huge amount of energy $\Delta U \approx 10^{39} - 10^{41}$ J is released during the symmetrization



Calculated total potential energies U vs *h* for the binary star KIC 9832227. The notation (0.8 M, 1 L), (0.5 M, 1 L), (0.8 M, 0.8 L), and (0.5 M, 0.5 L) means that the calculations are performed with the losses of the total mass M and orbital angular momentum $L = L_i$ by (20%, 0%), (50%, 0%), (20%, 20%), and (50%, 50%), respectively. The arrows show the corresponding initial η_i for binary stars.

A spectacular case is KIC 9832227, which was predicted to be merged in 2022, enlightening the sky as a red nova. For this system (η_i= 0.63 < η_b= 0.84), we conclude that a fast merger is excluded. Instead, the di-star is driven towards mass symmetry. Matter is transferring from a heavy star to a light one, and the relative distance between two stars and the period of the orbital rotation decreases. A huge amount of energy $\Delta U \approx 10^{41}$ J is released during the symmetrization.

So the source of expansion of a binary galaxy is the transfer of matter from a lighter component to a heavier one. A necessary and sufficient condition for this is the fulfillment of the inequality

$$r_{mi} > \frac{0.15\left(R_{1i}^{5/2} + R_{2i}^{5/2}\right)^{22/5}}{R_{1i}^{5} R_{2i}^{5}}.$$

The mechanism presented can be generalized for multiple galaxies, groups of galaxies, and galaxy associations.

Based on the Regge-like laws, we demonstrated that all possible binary stars or binary galaxies, regardless of their mass asymmetry, satisfy the Darwin instability condition $(S_1 + S_2 \geq \frac{1}{3}L)$, which contradicts observations. This output is not sensitive to model parameters. Therefore, we should look for another mechanism that triggers the merger of binary contact components.

If the fission hypothesis is not valid, then the only possible conclusion can be the assumption of a common origin of the components of a binary star from a pre-stellar state of matter. Thus, some stars likely arise during the formation of stellar groups in the form of pairs, triplets, quartets, etc. The observed excess of binary stars in the stellar associations suggests that these binary stars transform into ordinary binary stars after leaving the associations.

Summary

- Mass asymmetry degree of freedom plays a comparably important role in space objects. In close di-star or di-galaxy systems, the coordinate η can govern the merger and symmetrization (due to the matter transfer) processes.

- If η is determined, for example, by observation, it is possible to draw a conclusion about the stellar or galactic structure.

- Two distinct evolution scenarios arise: if $|\eta_i| < \eta_b$, the system is driven to the symmetric configuration (towards a global minimum of the potential landscape). However, if $|\eta_i| > \eta_b$, the binary system evolves towards the mono-object system.

- Symmetrization of a binary system ($|\eta_i| < \eta_b$) due to the matter transfer is one of the important sources of conversion of gravitational energy into other types of energy in the universe.

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