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W UMa-type Contact Close Binary Systems and Their Stability

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Close binary systems

- spectroscopic and eclipsing binaries

- stars are not independent, their influence each other - different evolution than in the case of isolated stars: mass transfer, mass loss, angular momentum loss from the system

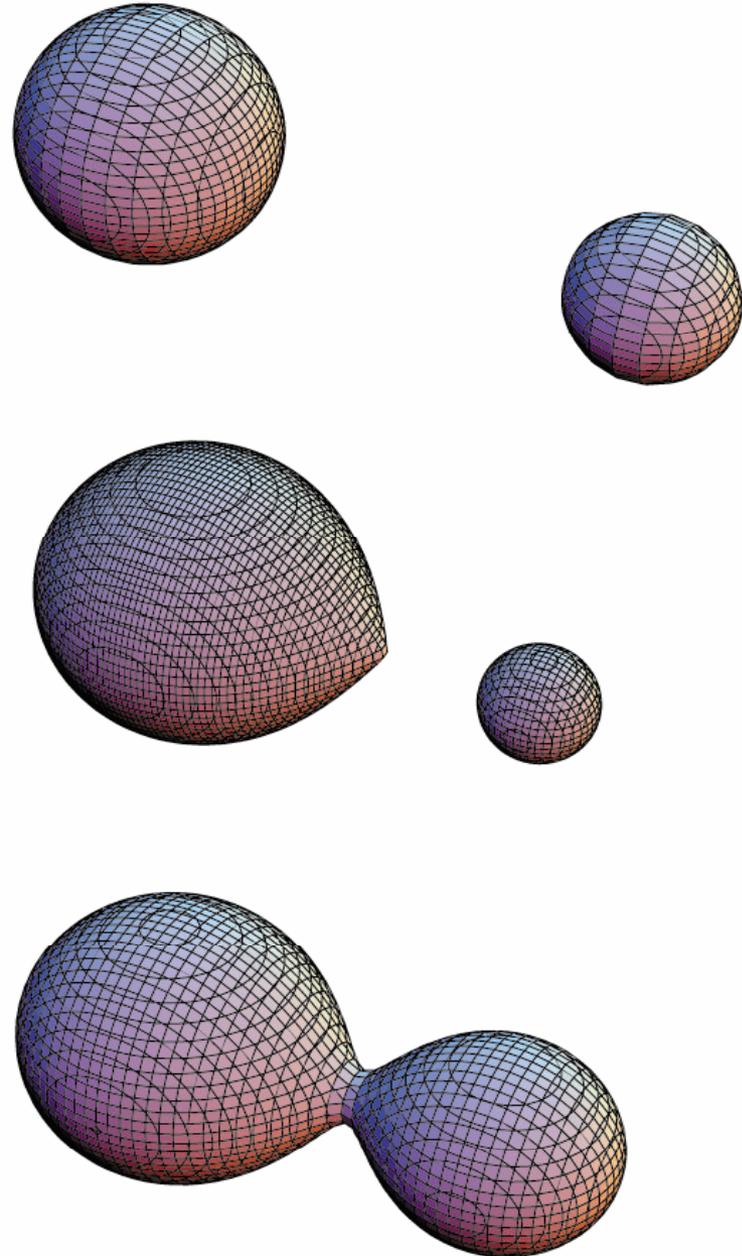
a) *detached*

b) *semi-detached*

c) *Contact*

- interesting systems, like **Cygnus X-1** (O star + black hole (**BH**)), X-ray binaries (semi-detached systems with neutron star (**NS**)) or cataclysmic variables (semi-detached systems with white dwarf (**WD**))

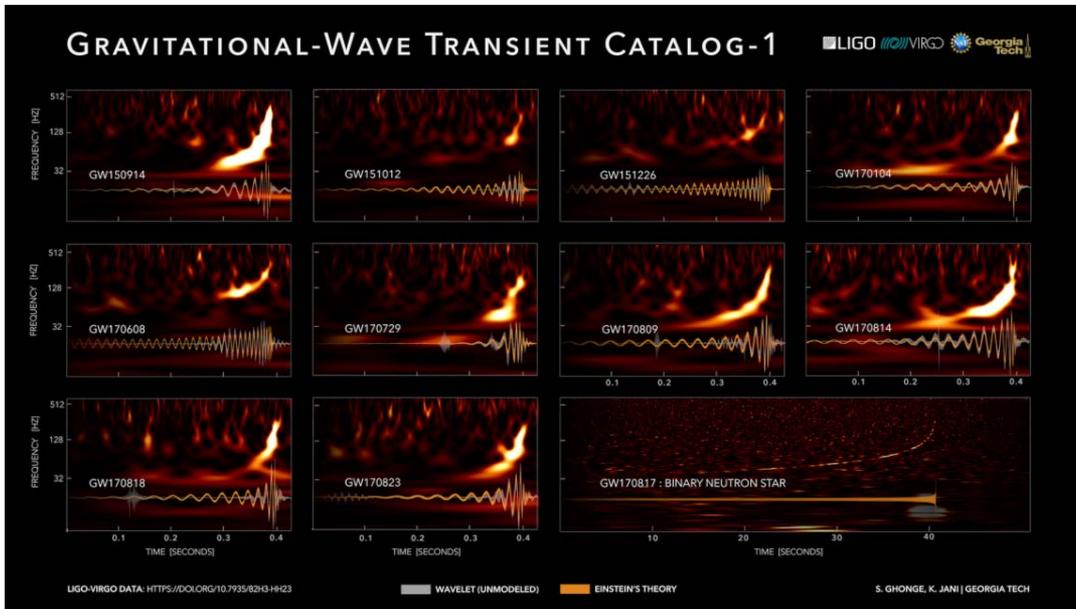
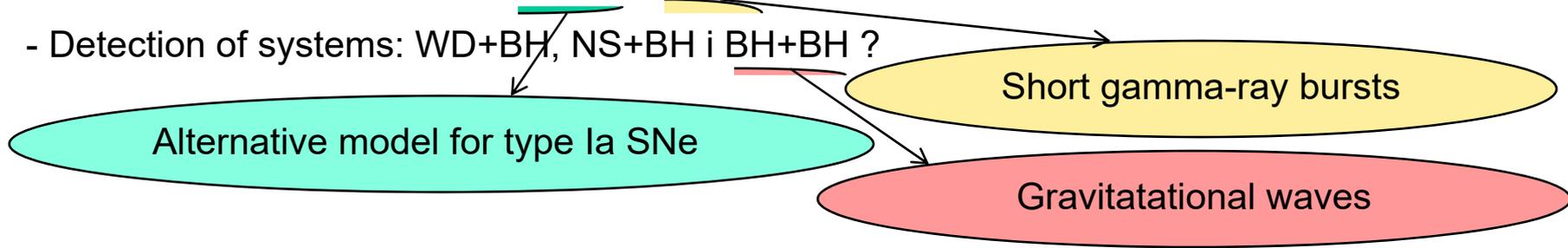
- > type Ia supernova (SN Ia)



- **Stellar mergers** are usually associated with compact binary systems – close binaries in which both components are **compact objects** (the final phases of stellar evolution): WDs, NSs and BHs

- Known systems: WD+WD, WD+NS, NS+NS

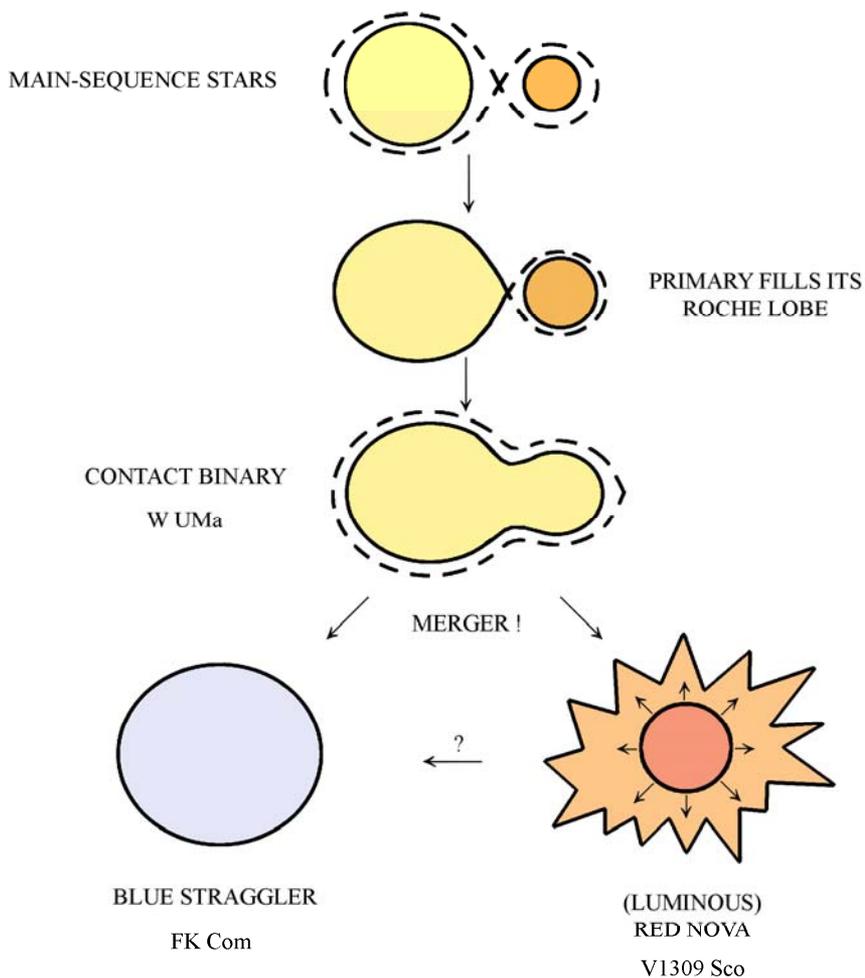
- Detection of systems: WD+BH, NS+BH i BH+BH ?



- most of detected signals come from massive BHs mergers, but there is a NS-NS merger GW170817 – kilonova AT2017gfo, perhaps another one GW190425, plus BH-NS mergers GW200105 and GW200115.

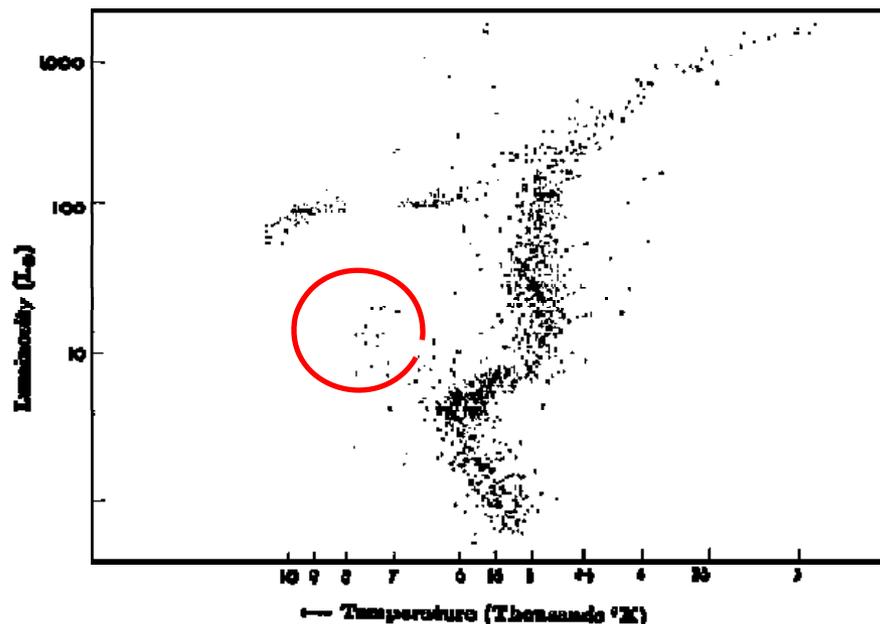
- But mergers can also happen with “normal stars”

CBS



- blue stragglers

Globular cluster M3



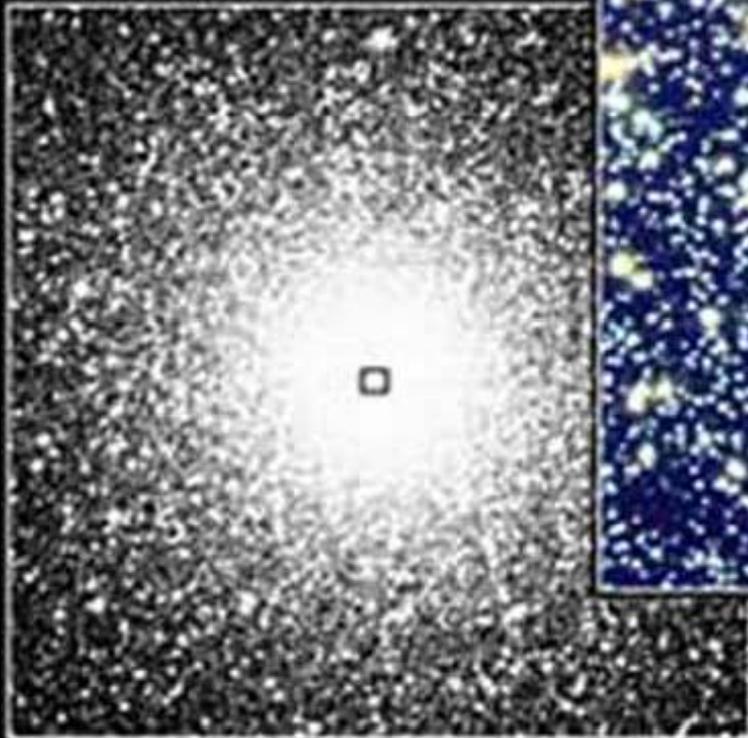
- alternatively (or predominantly) blue stragglers in old open clusters may form via mass-transfer from an AGB or RGB companion (Leiner et al. 2019, 2021)

- direct collisions?

Blue stragglers



Ground



HST

Interesting systems

V838 Mon

- atypical nova, (luminous) red nova?
- the eruption on a main sequence B stars in a close binary orbit with another B star, resulting in a cool (L-type) supergiant, $L \sim 10^4 L_{\odot}$, $R \sim 10^3 R_{\odot}$
- evolution of light echo
- merger in a triple system ([Kaminski et al. 2021](#))



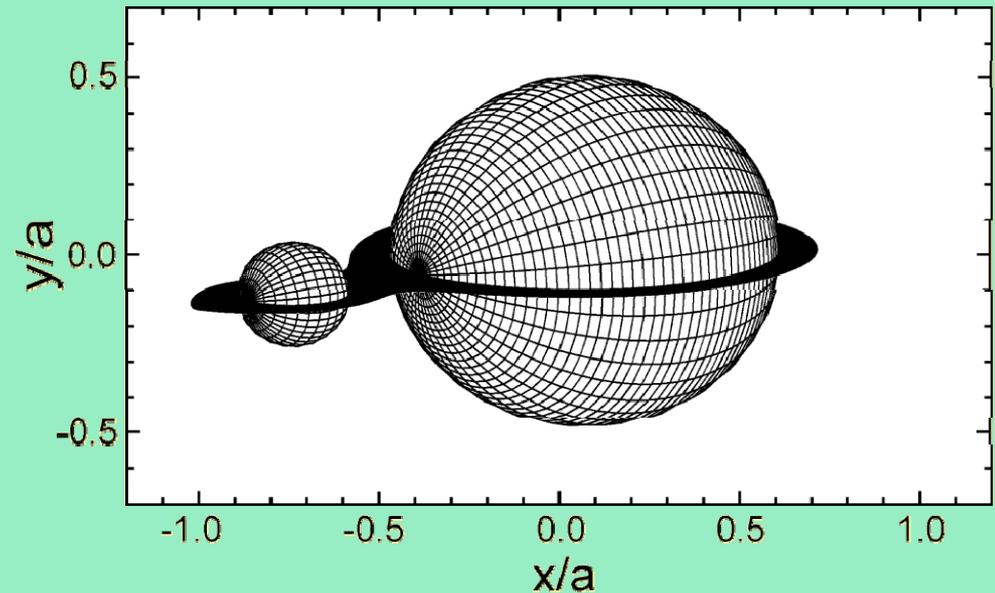
V1309 Sco

- red nova, OGLE observations 2001 – 2008 (outburst)
- Roseta stone of contact binary mergers ([Tylenda et al. 2011](#))
- K-type progenitor, initial period of 1.4 d with exponential decay $P \sim \exp(\tau/(t-t_0))$
- search for similar systems ([Kurtenkov 2017](#), [Wadhwa et al. 2021](#), [2022a,b](#), [Li et al. 2022](#))

Interesting systems

AW UMa

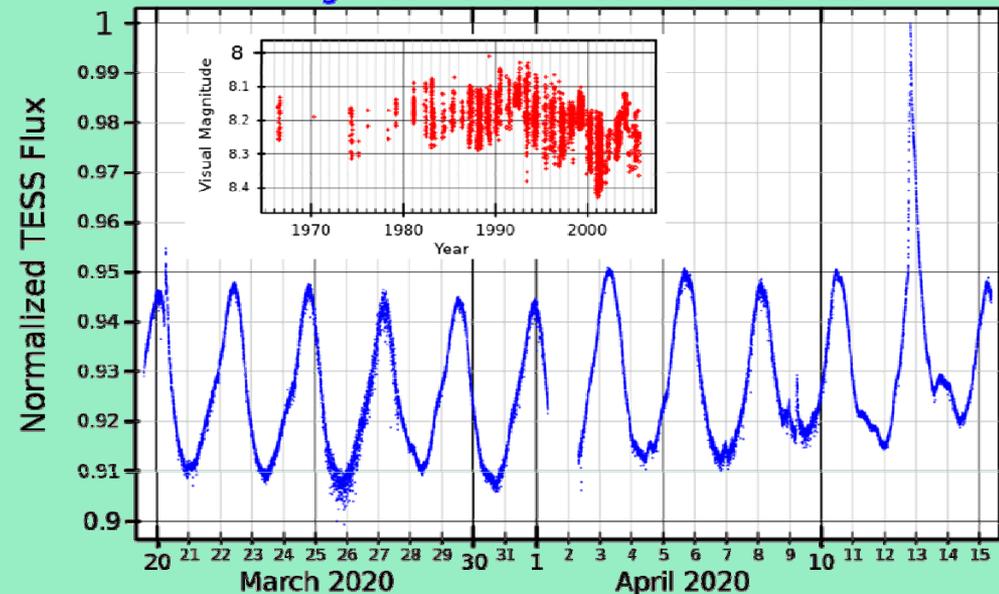
- Paczynski's star, discovered in 1964
- Extremely low mass ratio $q=0.075$ (Rucinski 1992)
- Pribulla & Rucinski (2008) find higher mass ratio $q = 0.1$ and suggest that AW UMa may not be a contact binary?



FK Com

- Prototype of a class of variables
- A giant (G4 III) with large cool spots, unusually fast rotation and magnetic activity
- May be the result of merger of a W UMa-type contact binary (Ayres et al. 2016 and ref. therein)
- long term variability (Panov & Dimitrov 2007)

A Light Curve for FK Comae Berenices



CBs of W UMa-type

- contact systems

- Roche model:

$$\Phi_{\text{eff}} = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{1}{2}\Omega^2 R$$

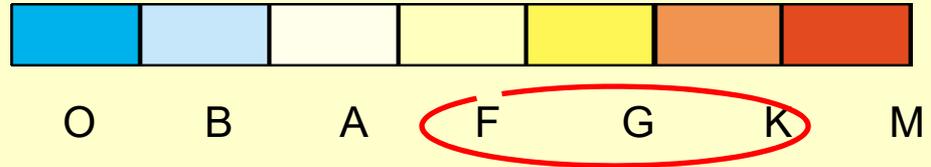
$$\Omega^2 = \frac{G(M_1 + M_2)}{a^3}$$

- spectral type: late F-K

- common convective envelope, nearly equal temperatures (although $q = M_2/M_1 \sim 0.5$)

- two sub-types: A and W

- primary components seems to be normal MS stars, secondaries are oversized for their ZAMS masses, and can be found *left* from the main-sequence (see e.g. [Hilditch 2001](#))

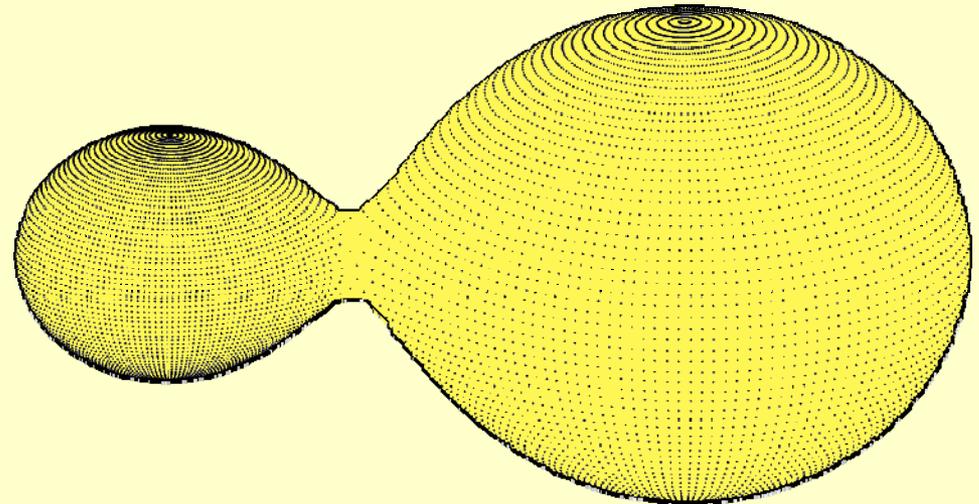


- critical equipotential surfaces (*Roche lobes*):

$$\Phi_{IL}, \Phi_{OL}$$

- degree of contact (*overcontact degree*):

$$f = \frac{\Phi - \Phi_{IL}}{\Phi_{OL} - \Phi_{IL}}$$



Dynamical evolution

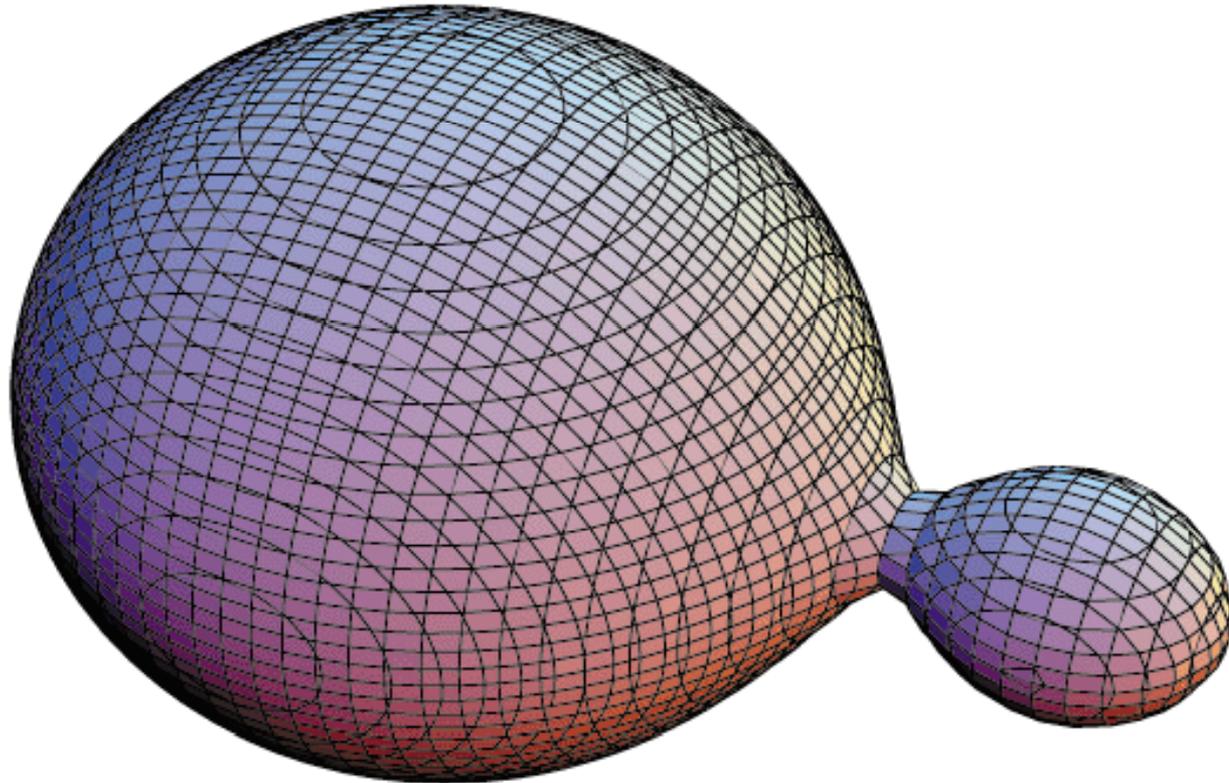
- driven presumably by angular momentum loss (AML)
- magnetic activity, starspots, magnetized stellar wind
- secular, tidal or Darwin instability



Sir George Howard Darwin (1845-1912)

- tidal forces → circulization and synchronization
- if the timescale for the synchronization is smaller than the AML timescale, system will remain synchronized and orbit will shrink until, at some critical separation, the instability sets in
- rotational and orbital angular momentum become comparable
- instability condition: $d J_{\text{tot}} = 0$ ($J_{\text{orb}} = 3 J_{\text{spin}}$)
(Hut 1980, Rasio 1995, Rasio & Shapiro 1995)
- MERGER!
W UMa → blue stragglers (Stepien & Kiraga 2015)
- a significant number of W UMa-type binary systems among blue stragglers in open and globular clusters (Kaluzny & Shara 1988).

Extremely low-mass ratio contact close binary systems



- there is a critical (minimum) mass ratio below which systems are likely to be unstable and merge

The minimum mass ratio for W UMa-type CBs

$$J_{\text{spin}} = k_1^2 M_1 R_1^2 \Omega + k_2^2 M_2 R_2^2 \Omega$$

$$J_{\text{orb}} = \mu a^2 \Omega = \frac{q \sqrt{GM^3 a}}{(1+q)^2}$$

$$\mu = M_1 M_2 / M, \quad M = M_1 + M_2, \quad q = M_2 / M_1$$

$$J_{\text{tot}} = J_{\text{orb}} + J_{\text{spin}}$$

$$dJ_{\text{tot}} = 0 \quad J_{\text{orb}} = 3J_{\text{spin}}$$

$$\frac{a_{\text{inst}}}{R_1} = k_1 \sqrt{\frac{3(1+q)}{q}} \quad \text{- critical separation (Rasio 1995)}$$

- k is dimensionless gyration radius which depends on the density distribution (for homogenous sphere $k^2 = 2/5$)

$$n = 3 \quad (\Gamma_1 = 4/3), \quad k^2 \approx 0.075$$

$$n = 1.5 \quad (\Gamma_1 = 5/3), \quad k^2 \approx 0.205$$

$$\text{- Sun} \quad k_{\odot}^2 = 0.059 \approx 0.06$$

$$\frac{R_{\text{IL}i}}{a} = \begin{cases} \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1+q^{-1/3})}, & i = 1 \\ \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}, & i = 2, \end{cases}$$

$$\frac{R_{\text{OL}i}}{a} = \begin{cases} \frac{0.49q^{-2/3} + 0.15}{0.6q^{-2/3} + \ln(1+q^{-1/3})}, & i = 1 \\ \frac{0.49q^{2/3} + 0.27q - 0.12q^{4/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}, & i = 2. \end{cases}$$

(Eggleton 1983, Yakut & Eggleton 2005)

$$\text{- } q_{\text{min}} = 0.071\text{-}0.077$$

$$\text{- AW UMa, } q = 0.075$$

(Paczynski 1964,
Rucinski 1992,
Pribulla & Rucinski 2008)

- contribution of the rotational AM of the secondary (Li & Zhang 2006, Arbutina 2007)

$$R_2 = R_2(R_1, a, q) \quad k_1^2 \neq k_2^2 \quad - q_{\min} = 0.094-0.109$$

- deformation of the primary due to rotation and companion – nonzero quadrupole moment – “apsidal motion constant” ratio (Arbutina 2009)

$$J_{\text{orb}} = \mu a^2 \Omega \quad J_{\text{spin}} = k_1^2 M_1 R_1^2 \Omega + \frac{2}{3} \left(\frac{\Omega^2}{3G} + \frac{M_2}{2a^3} \right) \bar{A}_1 \Omega \quad \bar{A}_1 = \frac{R_1^5 \bar{Q}_1}{1 - \bar{Q}_1}, \quad k_{\text{AM}} = \frac{1}{2} \frac{\bar{Q}}{1 - \bar{Q}}$$

$$\Omega^2 = \frac{GM}{a^3} \left(1 + \frac{\bar{A}_1 \omega_1^2}{2GM_1 a^2} + \frac{3\bar{A}_1 M_2}{M_1 a^3} + \frac{\bar{A}_2 \omega_2^2}{2GM_2 a^2} + \frac{3\bar{A}_2 M_1}{M_2 a^3} + \frac{3GM}{c^2 a} \right). \quad \omega_1 = \omega_2 = \Omega$$

- structure of the primary (k depends on the central condensation)

$$\begin{aligned} \rho \nabla \Phi_{\text{eff}} &= -\nabla P, \\ \Delta \Phi_{\text{eff}} &= 4\pi G \rho - 2\Omega^2, \\ P &= K \rho^{1+1/n}, \end{aligned} \quad \begin{aligned} \Phi_{\text{eff}} &= \Phi - \frac{1}{2} \Omega^2 \rho^2 - \frac{GM_2}{r_2} \\ \Omega &= \sqrt{GM/a^3}. \end{aligned}$$

- “spherical symmetry”, $r \rightarrow R$ volume radius, see Eggleton (2006)

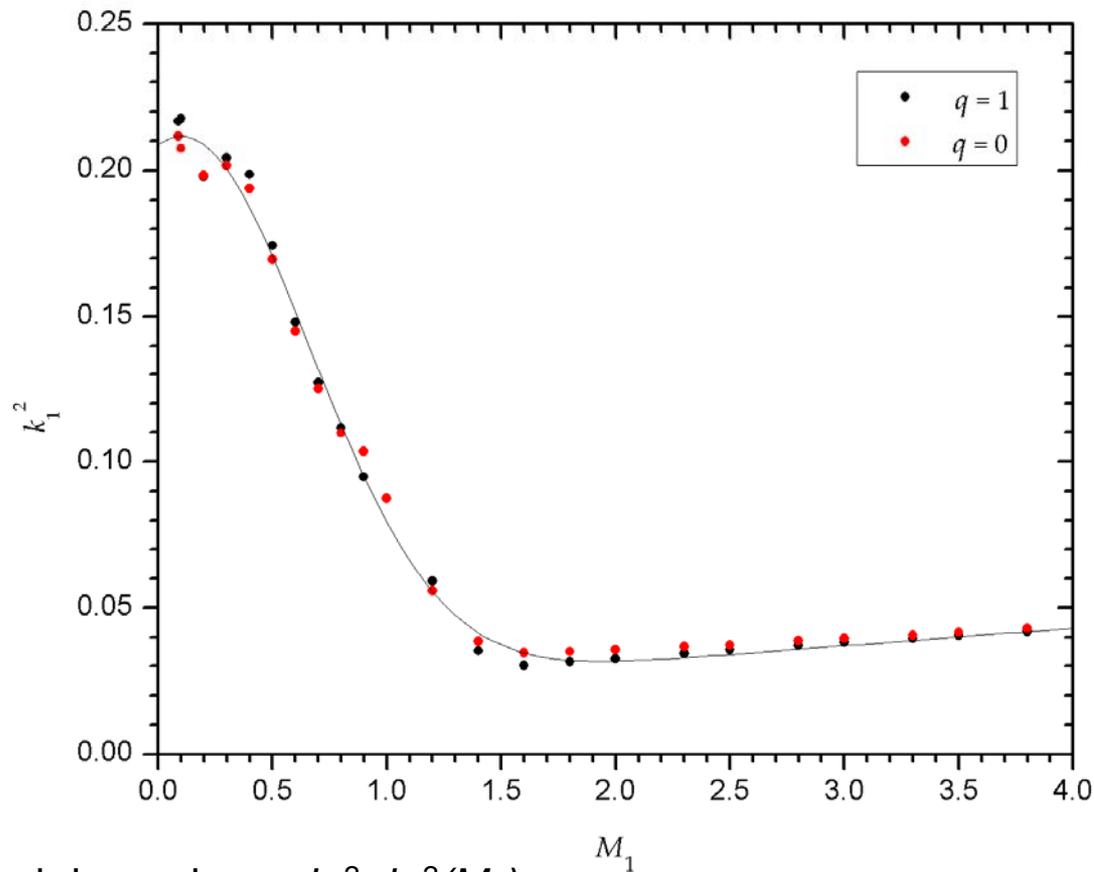
$$- q_{\min} = 0.070-0.074$$

- we should take into account mass dependence $k=k(M)$ (Wadhwa et al. 2021, 2022a,b, 2023a,b)

$$k_1 = -0.2392(M_1/M_\odot) + 0.527 \quad (0.6M_\odot < M_1 < 1.4M_\odot)$$

$$k_2 = -0.1985(M_2/M_\odot) + 0.485 \quad (0.09M_\odot < M_2 < 0.2M_\odot)$$

- for data from Landin et al. (2009)

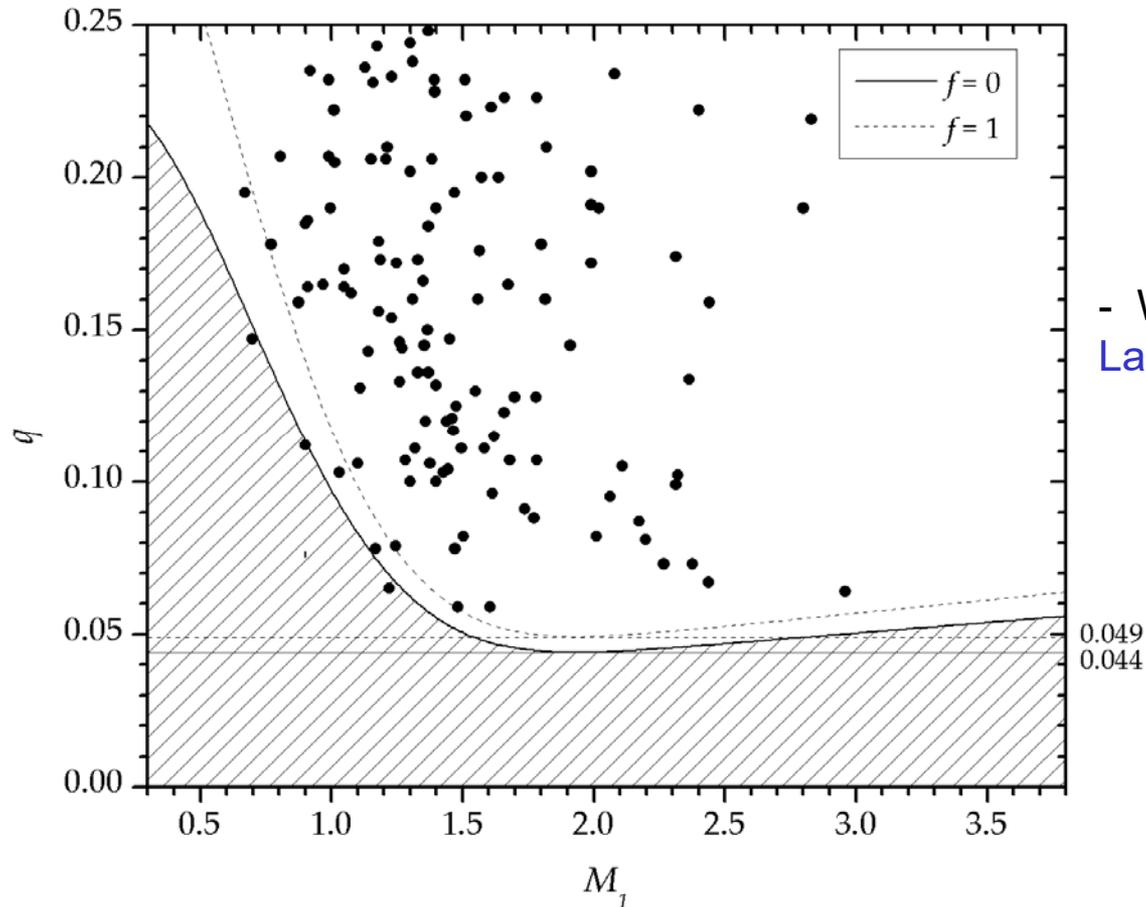


- improved dependence $k_1^2=k_1^2(M_1)$

- the instability mass ratio can be found for a given f and M_1

$$\Phi_{\text{eff}} \propto 1/R, \quad f = f(q, a/R), \quad f_1 = f_2 \rightarrow R_2 = R_2(R_1, a, q)$$

$$\frac{dJ_{\text{tot}}}{d(a/R_1)} = 0 \rightarrow q_{\text{inst}} = q_{\text{inst}}(M_1, f)$$



- WUMaCat data,
Latković et al. (2021)

- metallicity dependence (Wadhwa et al. 2024), are the comp. MS stars (Jiang et al. 2010)?

Work in progress...

THANK YOU!