Binary Evolution of Massive Stars and Supernovae

Omar G. Benvenuto

Instituto de Astrofísica de La Plata

Facultad de Ciencias Astronómicas y Geofísicas

Paseo del Bosque S/N

1900 La Plata, Argentina

obenvenu@fcaglp.unlp.edu.ar

-Dedicated to the memory of my mother-

Assumptions

- We treat the problem in 1D: Neglect all effects due to the departure from sphericity
- The orbit of the pair is assumed circularized and synchronized
- Usually irradiation from one star on the companion is neglected
- Most calculations ignore stellar rotation and only consider the orbital angular momentum

Assumptions

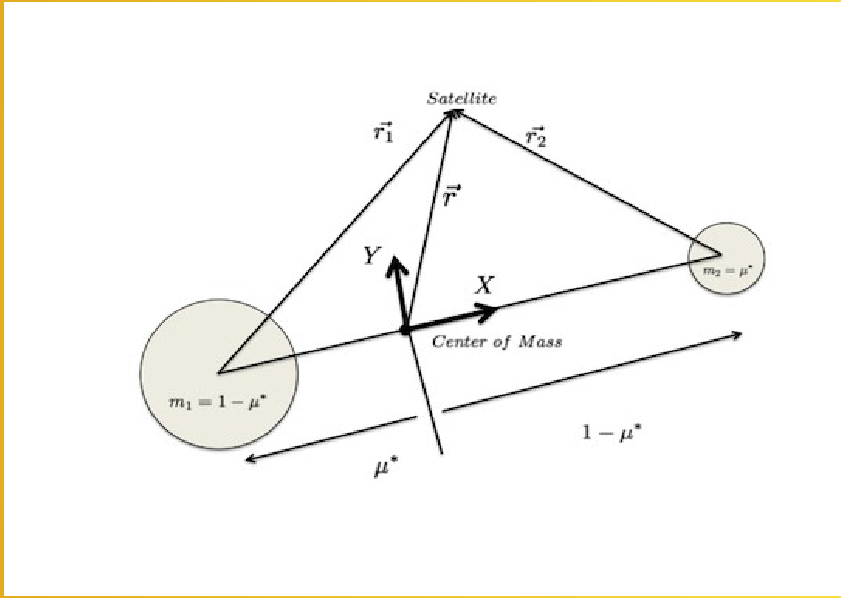
- Then, there is an upper limit for the volume for a star in hydrostatic equilibrium: The Roche Lobe
- Usually it is considered that the Lobe has a volume given by

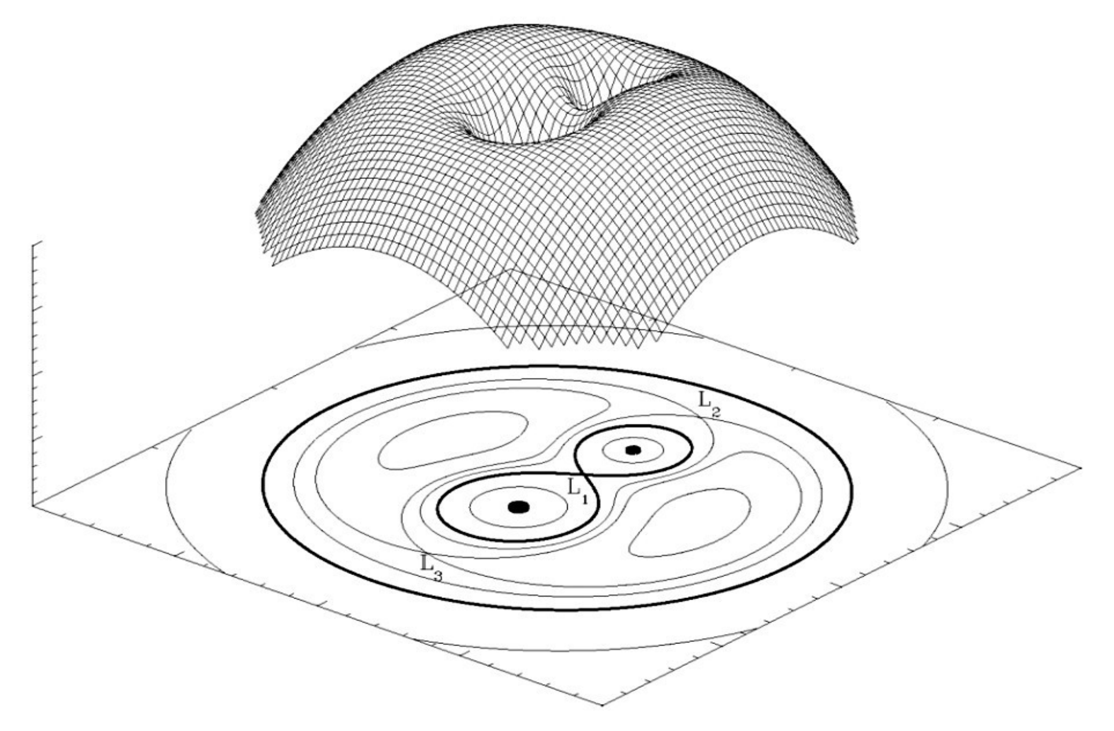
$$R_L = \frac{0.49\, q^{-2/3}}{0.6\, q^{-2/3} + \ln(1 + q^{-1/3})} A$$

(Eggleton 1983), where $q \equiv M_2/M_1$

- If the primary (most massive component) fills the lobe, the stellar surface reaches the Lagrangian Point L_1

Restricted Three Body Problem





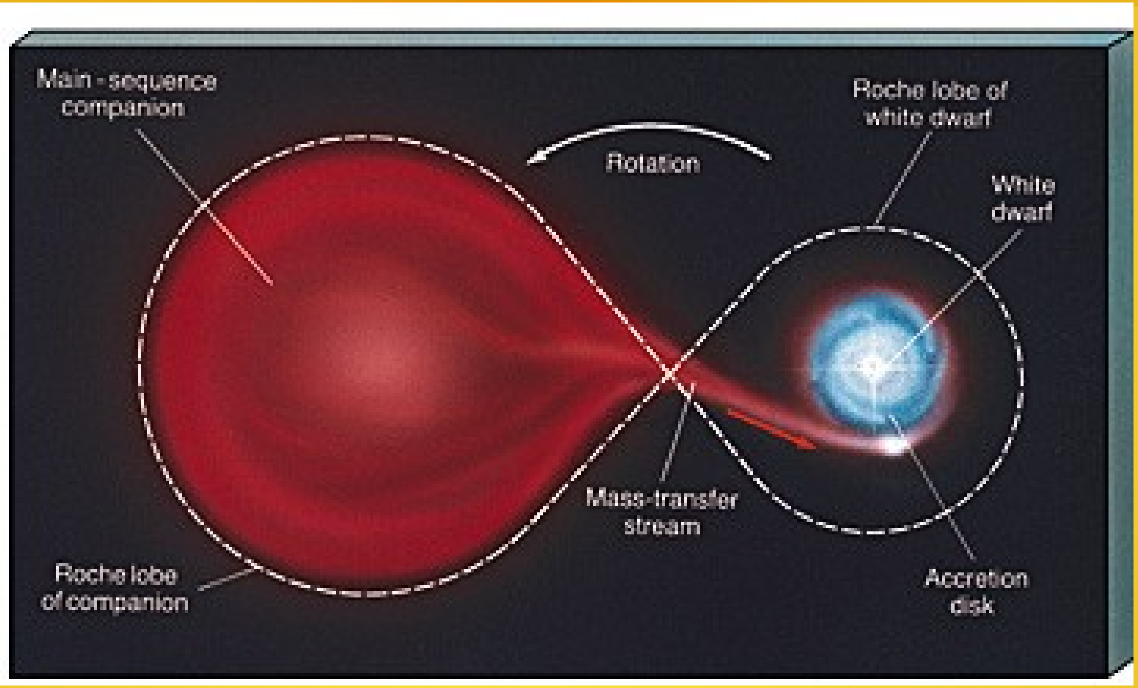
$$V(x,y,z) = \frac{GM_1}{\xi_1} + \frac{GM_2}{\xi_2} + \frac{\omega^2}{2}(x^2 + y^2);$$

$$\xi_i = \sqrt{(x - x_i)^2 + y^2 + z^2}$$

Assumptions

- At L_1 the gradient of the effective potential is zero, pressure dominates and the star undergoes mass and angular momentum transfer.
- This is the Roche Lobe OverFlow (RLOF)
- RLOF occurs if the orbit shrinks due to angular momentum losses (e.g. by gravitational wave radiation) or if stars swell enough due to nuclear evolution
- If only one component fills its lobe it is a semidetached system
- If both components fill their lobes, it is a contact binary

A Semi-Detached Binary



Classes of Mass Transfer

- Class A: Primary undergoes RLOF during core hydrogen burning
- Class B: RLOF after hydrogen core exhaustion but prior to helium ignition
- Class C: RLOF after helium core exhaustion

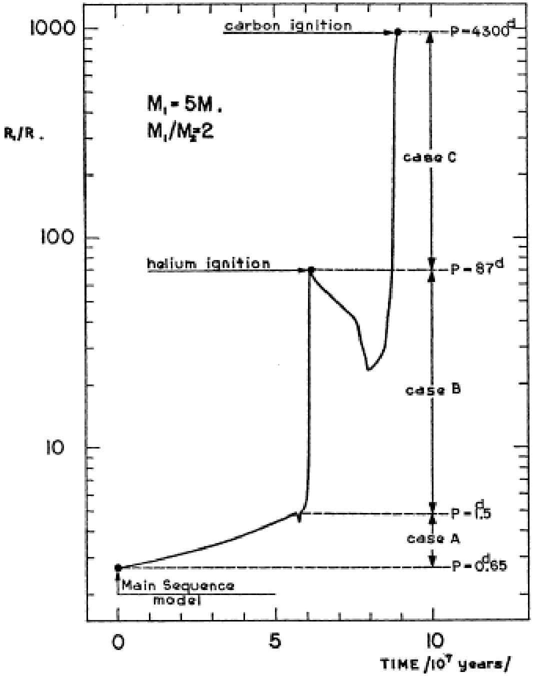


FIGURE 1. The time variation of the radius of a 5 $M_\odot$ star. The ranges of orbital periods corresponding to the evolution with mass exchange in cases A, B, and C are indicated. A mass ratio of $M_1/M_2=2$ is adopted.

A Binary Evolution Model for the Progenitor

- Stellar code: Benvenuto & De Vito (2003)

  If detached: standard Henyey code

  If semi-detached: modified Henyey code with Mdot computed implicitly together with the structure of the donor and the orbit
- Standard updated physics
- Rotation is not considered

The Equations of Stellar Evolution

$$\frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4} \tag{1}$$

$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi\rho r^2} \tag{2}$$

$$\frac{\partial L_r}{\partial M_r} = \varepsilon_{nuc} - \varepsilon_\nu - T\frac{\partial S}{\partial t}\bigg|_{M_r} \tag{3}$$

$$\frac{\partial T}{\partial M_r} = \nabla\frac{T}{P}\frac{\partial P}{\partial M_r} \tag{4}$$

$$\nabla = \nabla_{rad} = \frac{3}{16\pi acG}\frac{\kappa L_r}{M_r T^3} \tag{5}$$

$$\nabla = \nabla_{conv} \tag{6}$$

$$M_r = M\left(1 - e^{\xi}\right) \tag{7}$$

$$\frac{\partial}{\partial t}\bigg|_{M_r} = \frac{\partial}{\partial t}\bigg|_{\xi} + \frac{d\xi}{dt}\bigg|_{M_r}\frac{\partial}{\partial \xi}\bigg|_{t} \tag{8}$$

$$\frac{d\xi}{dt}\bigg|_{M_r} = \frac{\dot{M}}{M}\left(e^{-\xi} - 1\right) \tag{9}$$

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} + \dot{M}_1\left(\frac{1}{M_1 + M_2} - \frac{2}{M_1}\right) + \dot{M}_2\left(\frac{1}{M_1 + M_2} - \frac{2}{M_2}\right) \tag{10}$$

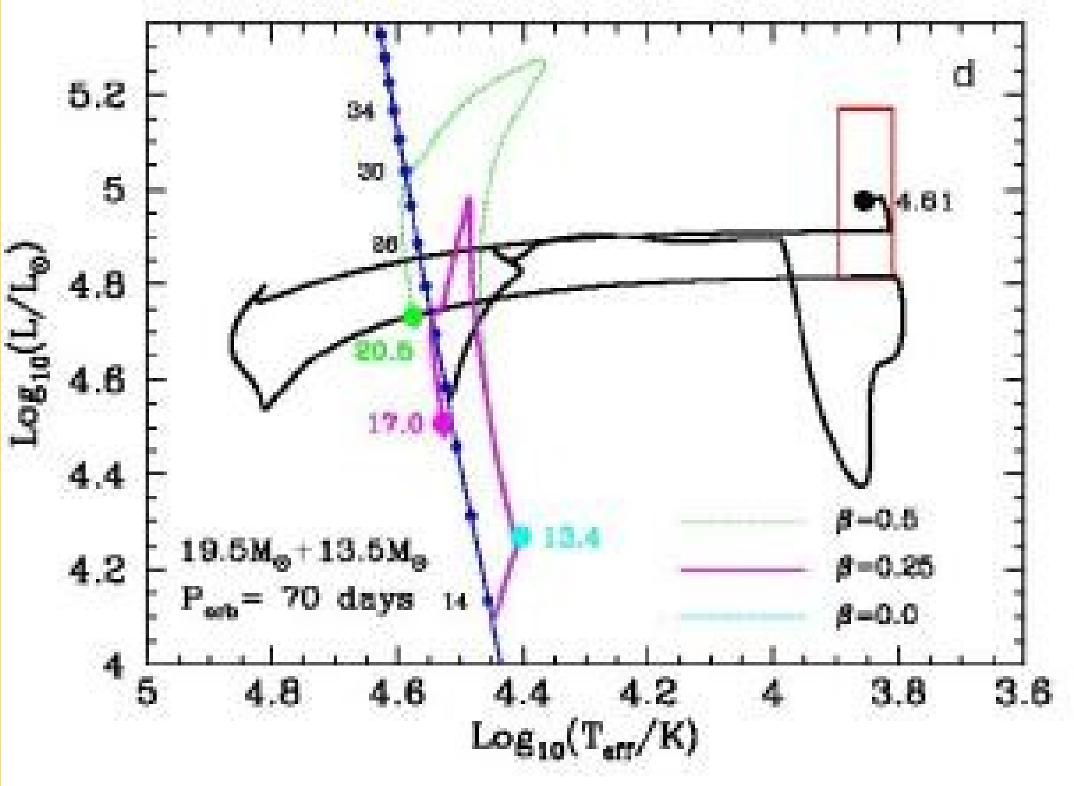
$$\dot{M}_2 = -\beta\dot{M}_1 \tag{11}$$

The Equations of Stellar Evolution

- Beta is considered as a free parameter, constant throughout the evolution (easy, but hard to consider it as realistic)

  If a progenitor of supernova is a YSG, it is easily accounted for by binary evolution

A Binary Progenitor for SN 2016gkg



Photometry

$$T_{eff} = 7250^{+900}_{-850}K$$

$$Log(\frac{L}{L_\odot}) = 5.10^{+0.17}_{-0.19}$$

$$R = 226^{+98}_{-73}R_\odot$$

Presupernova Model

$$M = 4.01M_\odot$$

$$M_H = 0.006M_\odot$$

$$M_{env} = 0.06M_\odot$$

$$X_{surf} = 0.21$$

$$R = 183R_\odot$$

$$P_{orb} = 631 days$$

Bersten, et al. 2018. Nature 554, 497

The Binary Progenitor of SN 2011dh

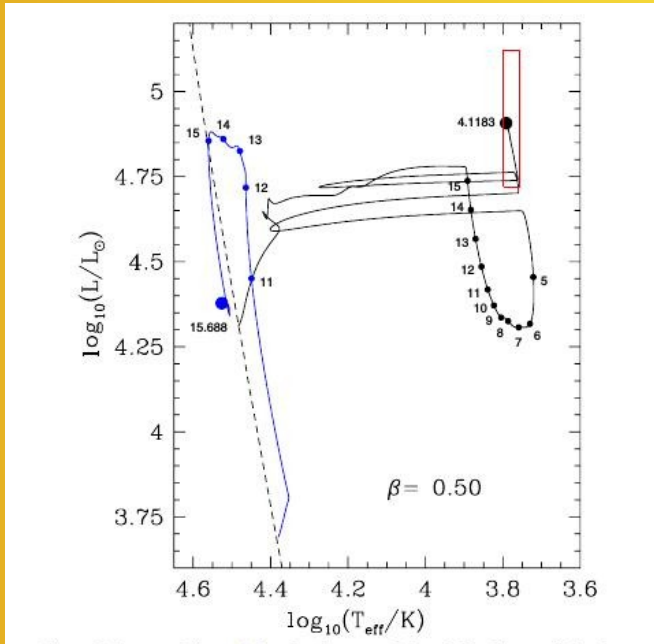
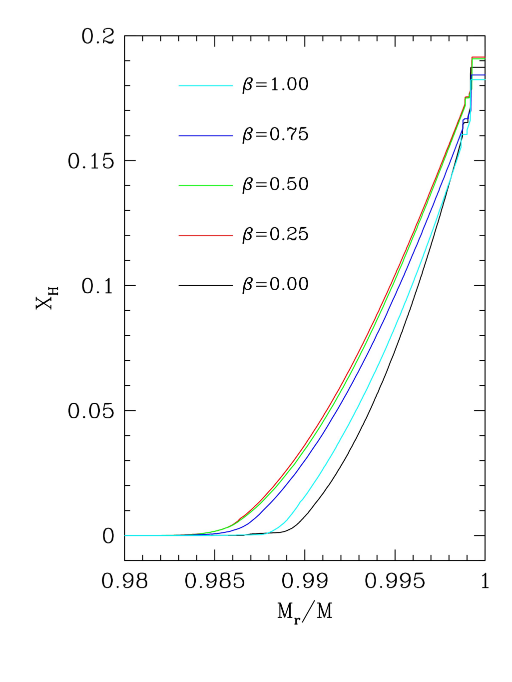
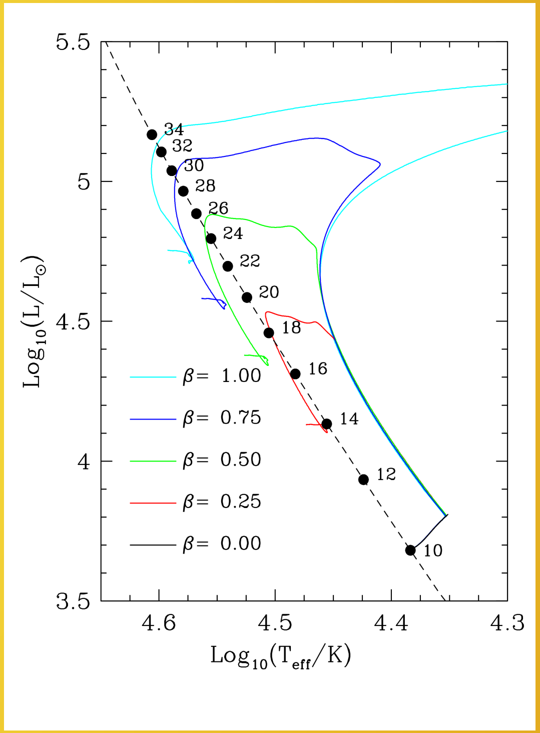


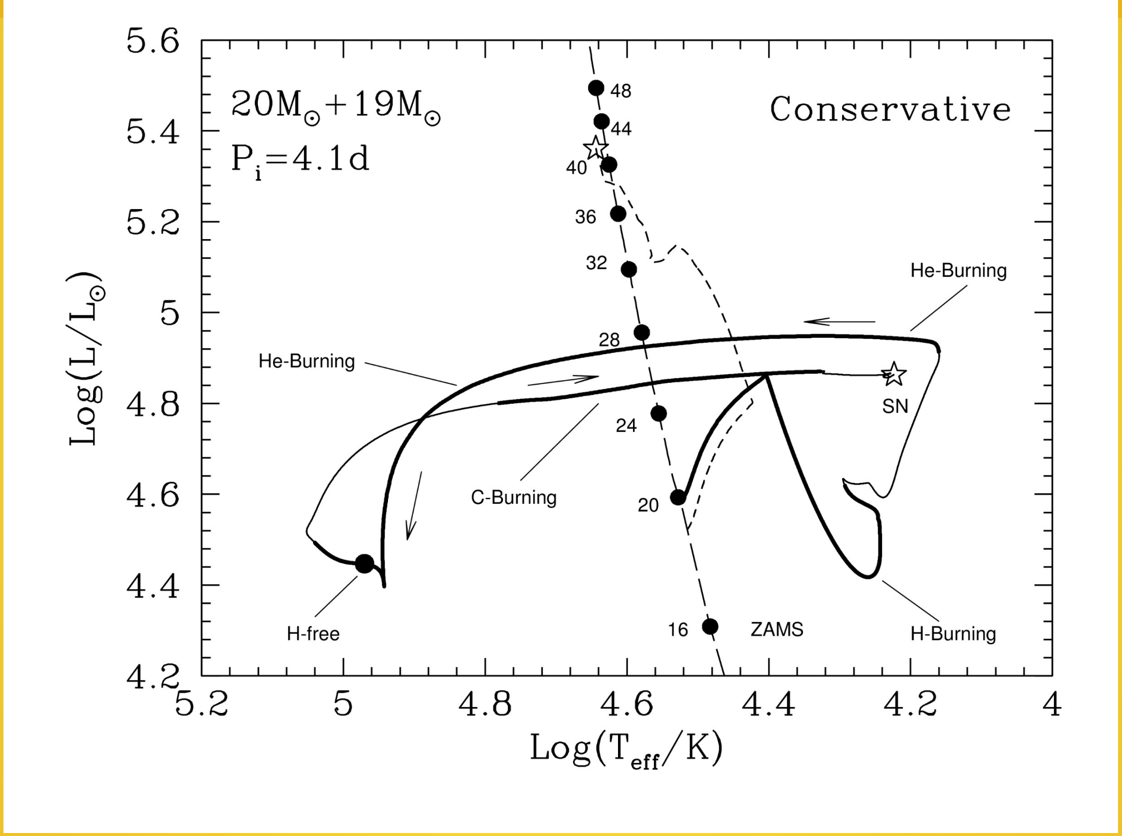
Figure 3. Same as Figure 1, but for the case of $\beta = 0.50$. Lines and dots have the same meaning as there.





Benvenuto, et al. 2013. ApJ 762, 74

The Case of IPTF 13bvn

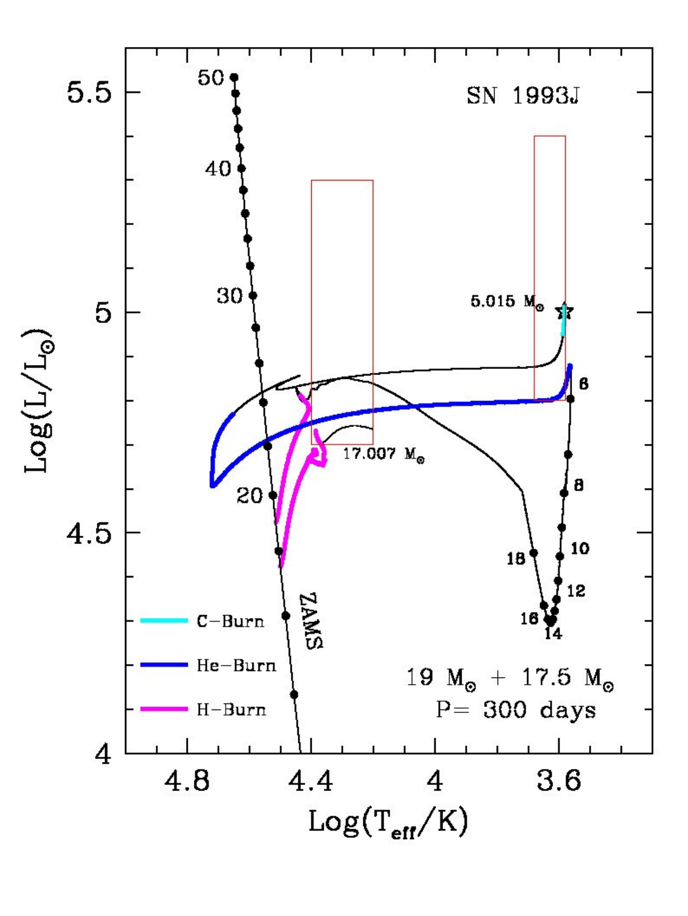


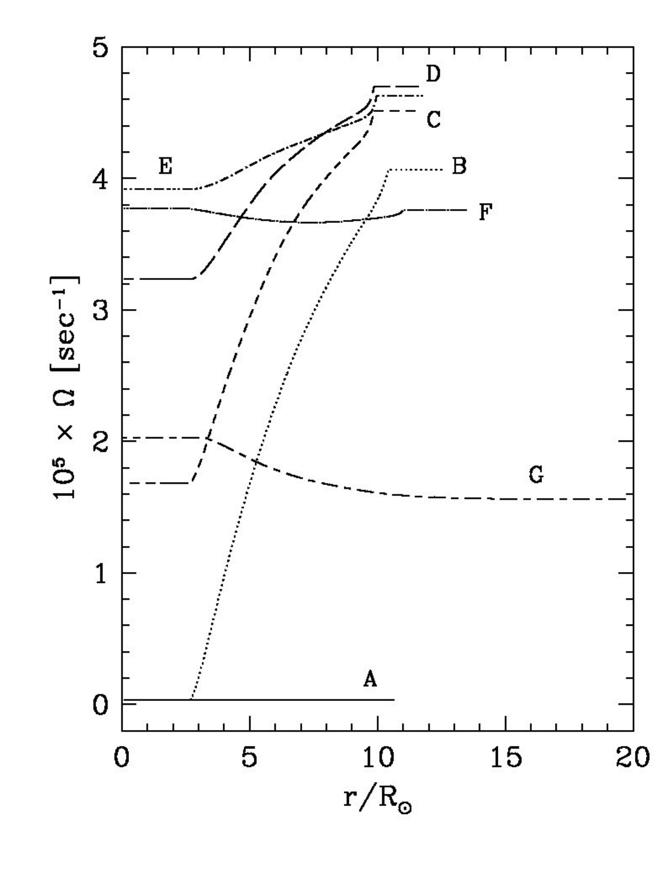
Bersten, et al. 2014. AJ 148, 68

Models With Rotation (preliminar)

- Consider shellular rotation and solve the equations of Zahn (1992). These are of fourth order in space, not easy to solve!
- Assume that the accretion disk forces the outermost layers of the accreting star to keplerian velocity.
- Angular momentum diffuses inwards, initially keeping angular velocity below critical
- Consider that critical rotation fully inhibits further accretion

Models With Rotation (preliminar)





How to Handle Accretion onto the Companion Star?

- Usually, material forms an accretion disk around the companion star
- Accreted material has a large specific angular momentum that speeds up rotation, even up to critical velocity
- What's happen since then on?
- To reach critical regime little accretion is enough.
- Paczyński (1991) showed that acretion may continue even then, but his model is a polytropic disk+star (mass goes inwards, angular momentum outwards)

- How is the evolution in a more realistic case? Not easy.
- This problem is central since otherwise we cannot predict the properties of the companion that should survive the companion explosion
- If we ask if binary evolution is fully predictive, we have to conclude that, at least at present, this is ***not*** the case

- It seems to me that sometimes observers largely underestimate the actual uncertainties still present in stellar modelling, especially in binary evolution.

Thanks to Nidia and the OC for the Invitation

Thank You For Your Attention!