Astrophysics of gravitational wave sources

Lecture 6: Binary star evolution

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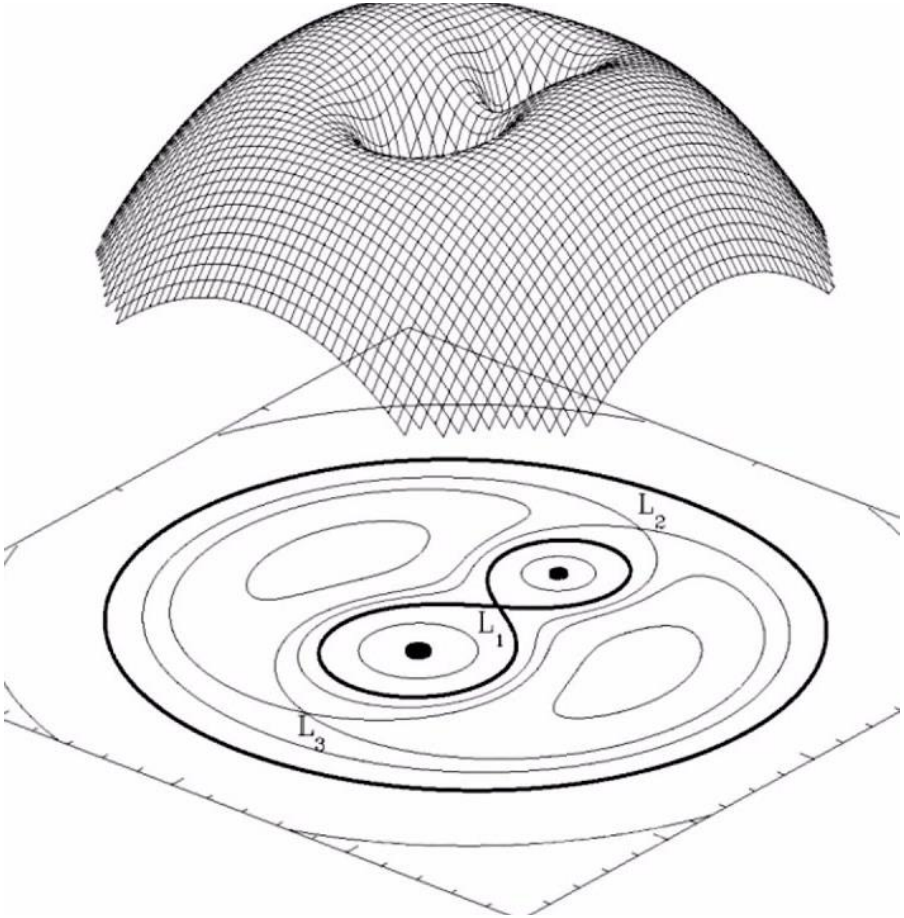
Order-of-magnitude astrophysics

Does a 15 solar mass star release more energy during its stellar lifetime or when it explodes as a supernova? Which form of energy release is likely to have more impact on the surrounding interstellar medium?

http://www.astronomy.ohio-state.edu/~dhw/Oom/questions.html

Roche potential



$$\frac{R_{\mathrm{L}}}{a} \equiv x_{\mathrm{L}}(q) \approx \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}, \qquad 0 < q < \infty,$$

$$\approx \frac{0.44q^{0.33}}{(1+q)^{0.2}}, \qquad 0.1 \lesssim q \lesssim 10.$$

(Eggleton's book)

Angular momentum of a binary star

$$R'_{\mathrm{L}} \equiv \frac{\mathrm{d}\log R_{\mathrm{L}}}{\mathrm{d}\log M_1} = (1+q)\cdot\left(\frac{\mathrm{d}\log R_{\mathrm{L}}/a}{\mathrm{d}\log q} + \frac{\mathrm{d}\log a}{\mathrm{d}\log q}\right)$$

$$\approx 2.13q - 1.67, \quad 0 < q \lesssim 50;$$

Darwin instability

Roche lobe overflow

$$\log R = \log R_0 + R'_{TE} \log \frac{M_1}{M_0} + \frac{t}{t_{NE}}$$

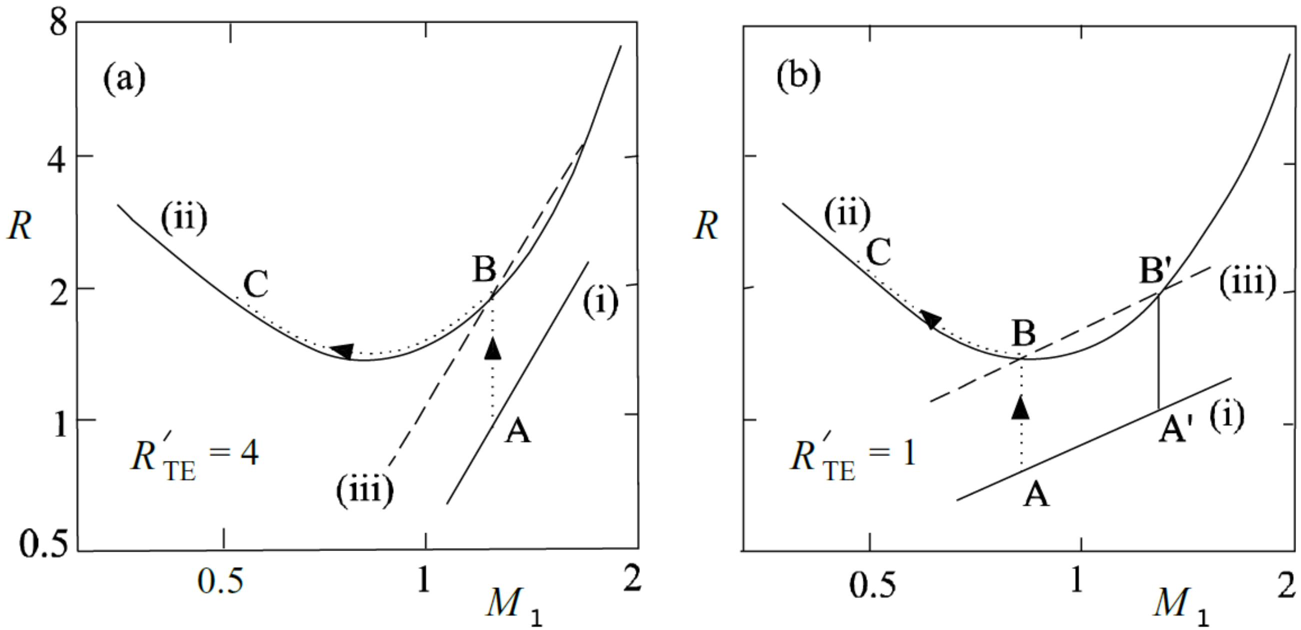


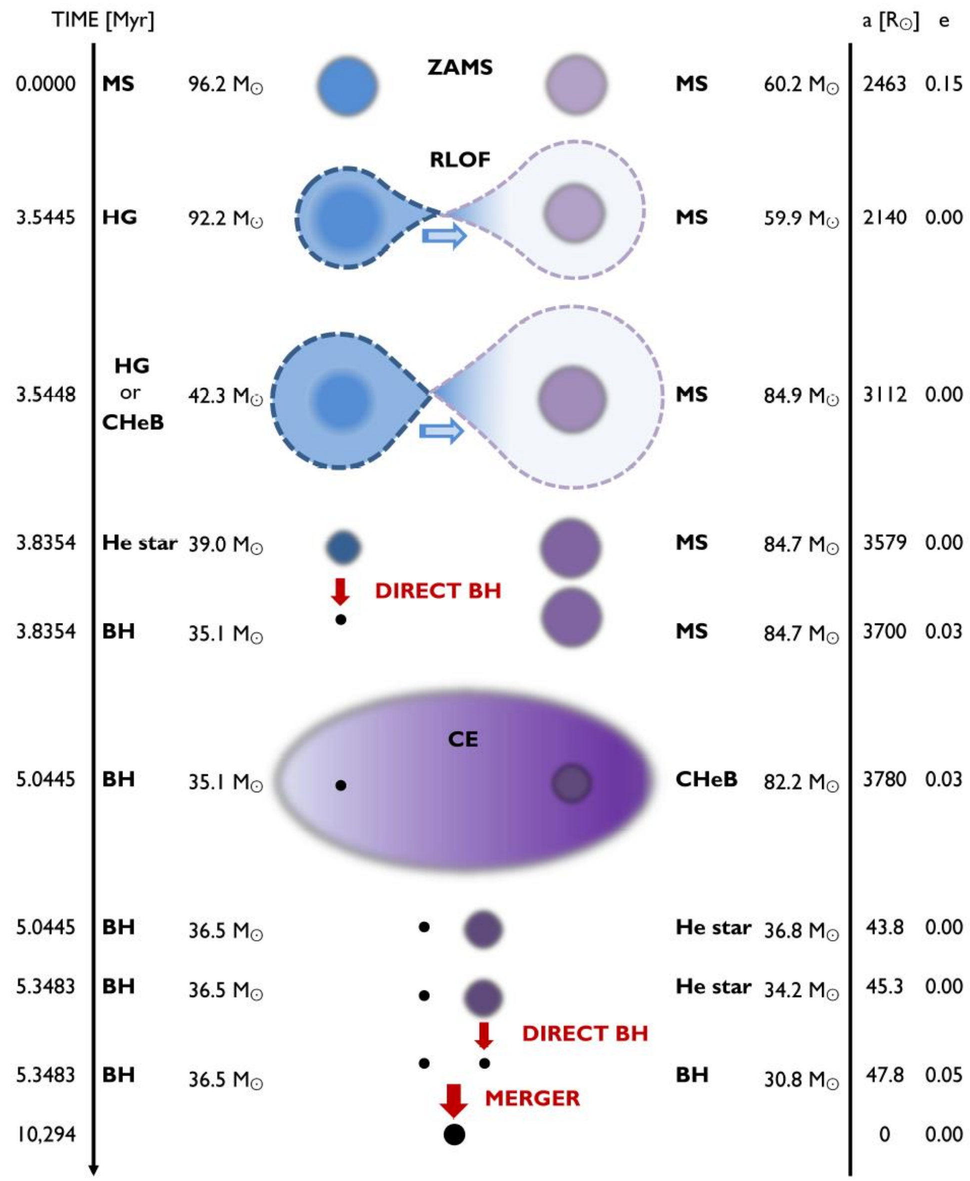
Figure 3.4 Schematic behaviour of Roche-lobe radius and stellar radius as functions of primary mass during evolution governed by the simplistic relation (3.52). Units are arbitrary, except that the total mass is 2 units. The curves are (i) the ZAMS radius, (ii) the Roche-lobe radius, (iii) the radius at time $t = t_{NE} \log 2$. The star starts on curve (i), at point A or A′, and evolves vertically until it reaches curve (ii) at B or B′. From B in either panel, it can proceed to evolve along curve (ii) to C, losing mass while still evolving on a nuclear timescale. In (b) it cannot do this from point B′, since curve (ii) is steeper than curve (iii) there.

$$\frac{d \log M_1}{dt} = -\frac{1}{t_{NE}} \cdot \frac{1}{R'_{TE} - R'_L}.$$

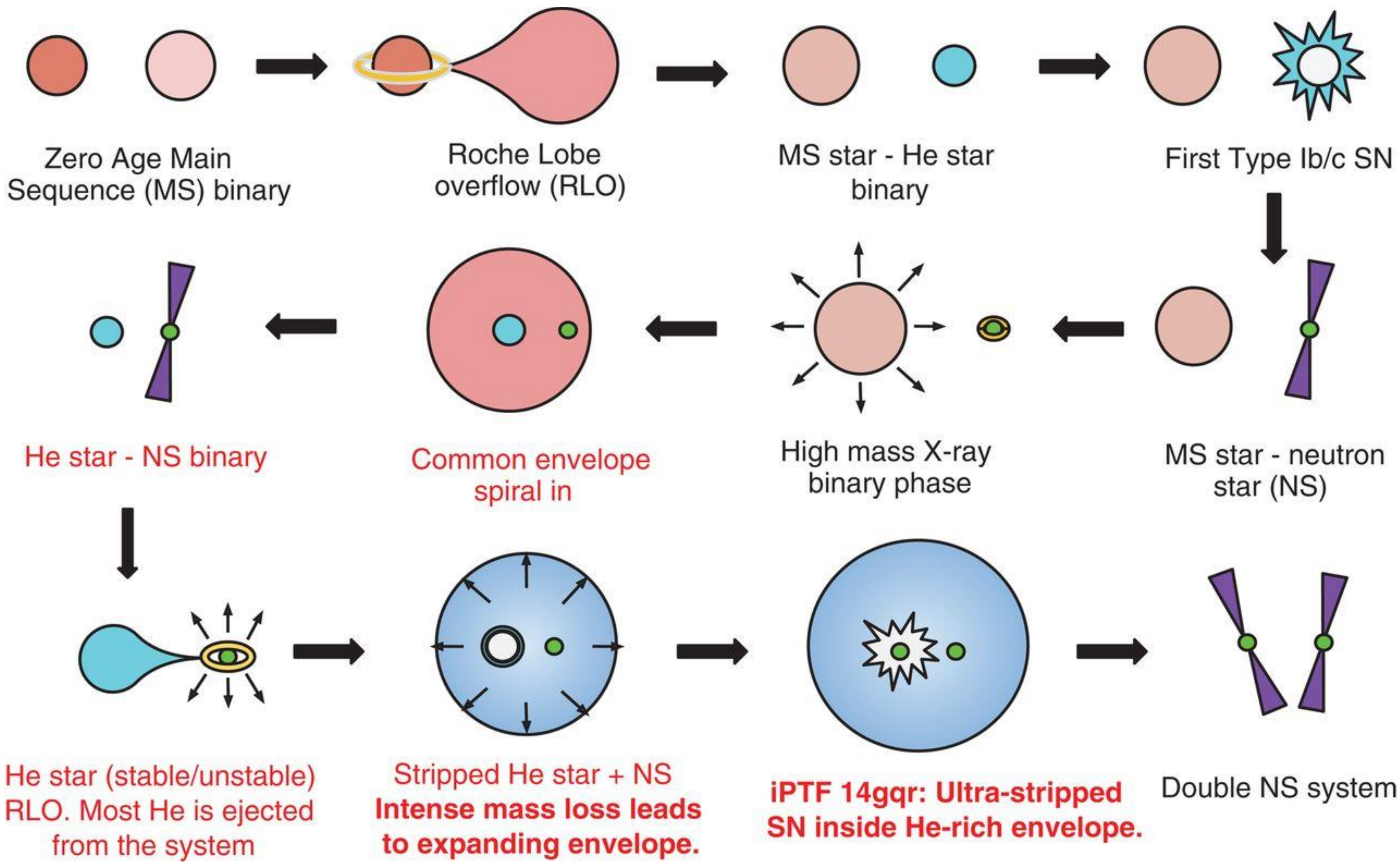
(Eggleton's book)

Roche lobe overflow

- Nuclear, thermal, dynamical timescale
- Conservative vs nonconservative evolution
- Nonconservative processes:
  - Stellar wind
  - Magnetic braking
  - Gravitational radiation
  - Tidal friction
  - Secular dynamics
  - (supernova, common envelope, cluster dynamics)



Belczynski et al. (2016)


Zero Age Main Sequence (MS) binary
Roche Lobe overflow (RLO)
MS star - He star binary
First Type Ib/c SN
MS star - neutron star (NS)
High mass X-ray binary phase
Common envelope spiral in
He star - NS binary
He star (stable/unstable) RLO. Most He is ejected from the system
Stripped He star + NS
Intense mass loss leads to expanding envelope.
iPTF 14gqr: Ultra-stripped SN inside He-rich envelope.
Double NS system

De et al. (2018)