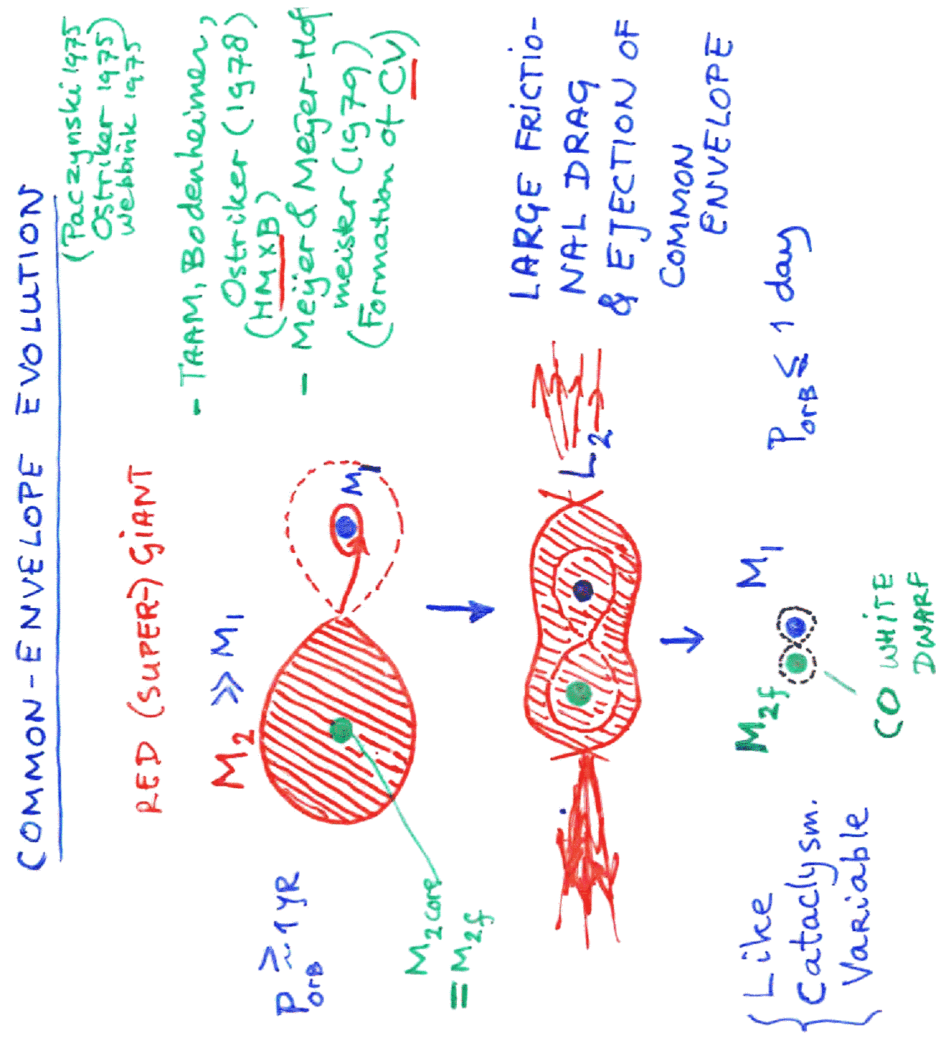
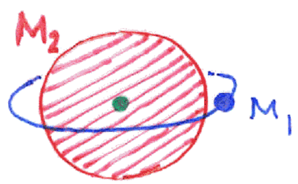


REASONS FOR COMMON-ENVELOPE FORMATION

LACK OF CO-ROTATION (Paczynski 1975, Ostriker 1975, Webbink 1975)

1. TIDAL INSTABILITY (G. Darwin 1895):

MOMENT OF INERTIA of GIANT > $\frac{1}{3}$ (MOM. OF Inertia BINARY)



[Requires $M_2 \gtrsim (5-10)\, M_1$]

2. UNSTABLE MASS TRANSFER:

$\tau_{transfer} \ll \tau_{thermal}$ (accretor)

THIS CAN BE DUE TO:

A. Mass Ratio $q = M_1/M_2 \ll 1$

($\tau_{th} \propto 1/M^2$) $\Rightarrow$ if $q < 0.5$: PROBLEM

OR B. CONVECTIVE ENVELOPE of DONOR EXPANDS UPON MASS LOSS

$P \propto \rho^{5/3} \rightarrow$ Polytrope $n = 3/2$

MASS LOSS ON DYNAMICAL TIMESCALE

$\tau_{\dot{M}} = 50^{min} (\rho_\odot / \rho_*)^{1/2}$

ROUGH ESTIMATE OF FINAL P_{orb}
(ENERGY ARGUMENT) Webbink '79

ASSUME: E_{bind} (ENVELOPE) ≃ LOSS OF ORBITAL ENERGY

$$\frac{G(M_{2f}+M_{2e})M_{2e}}{\lambda\, a_1 r_{L_2}} = \alpha_{CE}\left\{\frac{G M_1 M_{2f}}{2a_2} - \frac{G(M_{2f}+M_{2e})M_1}{2a_1}\right\}$$

λ: wheight factor < 1; $a_1 r_{L_2} = R_{L_{2,1}}$

$$\therefore\ a_2 = a_1 \frac{M_1 M_{2f}}{M_{2f}+M_{2e}} \Big/ \left(M_1 + \frac{2M_{2e}}{\alpha_{CE}\lambda r_{L_2}}\right)$$

EXAMPLE: Meyer & Meyer-Hofmeister (1979):

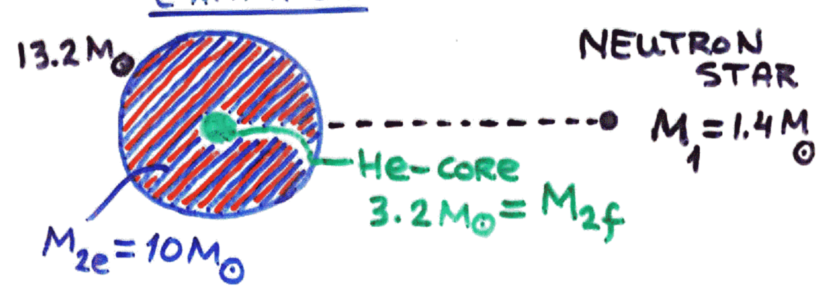
$\alpha_{CE}=1$, $M_1 = M_{2f} = 1$, $M_{2e} = 4$, $r_{L_2} = 0.5$, $\lambda = 0.5$

$$\therefore\ \frac{a_2}{a_1} = \frac{1}{5}\Big/\left(1+\frac{8}{0.25}\right) = 1/_{5\times 33} = 1/165 \quad \text{for } \alpha=1$$

$$P_2/P_1 = (a_2/a_1)^{3/2}\left(\frac{M_\odot}{M_f}\right)^{1/2} = 1/1300$$

if $P_1 \simeq 650^d \Rightarrow P_2 = 0.5^d$

EXAMPLE



$\alpha = 1 \Rightarrow a_2/a_1 = 1/250$

$\therefore$ For $\left\{\begin{array}{l} a_1 = 2.5\ AU \\ P_1 = 1.03\ YR \end{array}\right\} \Rightarrow a_2 = 0.01\ AU = 2.16\ R_\odot$, $P_2 = 4.09\ HR$

$R_{Roche}(M_{2f}) = 0.98 R_\odot$

$R_{M_{2f}}$ (He-star) < 0.5 $R_\odot$

$a_2 = 2.2\ R_\odot$

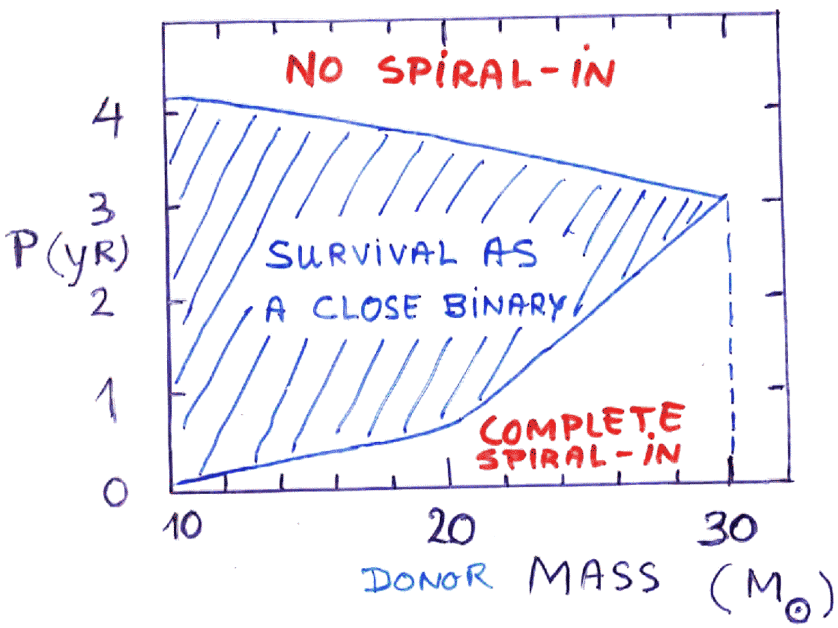
$P_2 = 4.09$ HR

He-star will finally explode

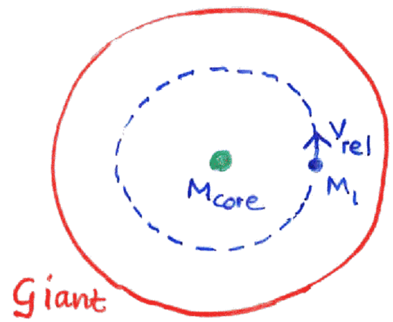
⇓

SHORT-PERIOD eccentric

OUTCOME OF COMMON-ENVELOPE EVOLUTION OF MASSIVE X-BINARIES (TAAM & BODENHEIMER 1992)



INCLUDES EFFECT OF STRONG WIND MASS LOSS OF SUPERGIANTS

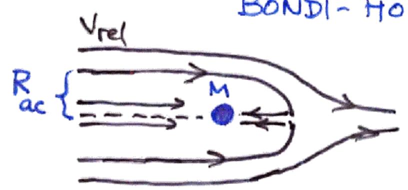


INGREDIENTS OF NUMERICAL MODEL CALCULATIONS

(e.g.: Taam et al. 1995; Terman et al. 1993 Podsiadlowski & co-workers, 2002 ⇒).

a) Energy dissipation: Frictional Drag

BONDI-HOYLE APPROXIMATION



$$L_{drag} \sim \dot{M} V_{Rel}^2$$

where:

$$\dot{M} = \pi R_{ac}^2 \rho V_{Rel}$$

$$R_{ac} = \frac{2GM_1}{V_{rel}^2 + c_s^2}$$

$$V_{rel} = V_{orb} - V_{env}$$

b) ORBITAL EVOLUTION: Loss of GRAV. Binding Energy

$$\frac{d}{dt}\left(\frac{G M_{core} \cdot M_1}{2a}\right) = - L_{drag}$$

N.B.: R_{ac} is mostly >> Radius of M_1

$$R_{ac} = \frac{M}{M_\odot}\left(\frac{620\,km/s}{V_{rel}}\right)^2 R_\odot$$

e.g. if $a = 1$ AU, $M_c = 2M_1$, $M_1 = 1 M_\odot \Rightarrow V_{rel} = 60\ \frac{km}{}$

Terman, Taam & Hernquist 1994, Ap.J. 422, 729

3D – SPH Simulation 4.67 $M_\odot$ RED GIANT + 0.94 $M_\odot$ DWARF

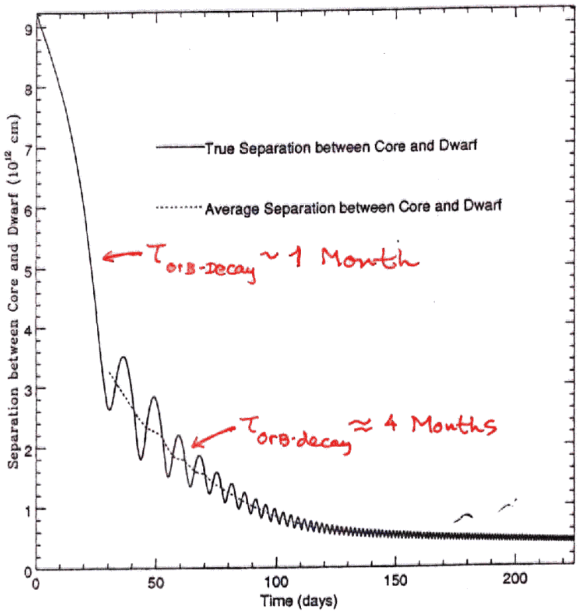


FIG. 1.—The variation of the orbital separation between the core of the red giant and the dwarf companion as a function of time. The solid curve corresponds to the actual separation between components, and the dashed line corresponds to the average separation. The separation is expressed in units of 10^{12} cm, and the evolution time is expressed in days.

$P_0 = 0.47$ YR ($a_0 = 1.07$ AU), $M_{core} = 0.62 M_\odot$

$R_{core} = 5.47 R_\odot$

Initial System in Co-Rotation

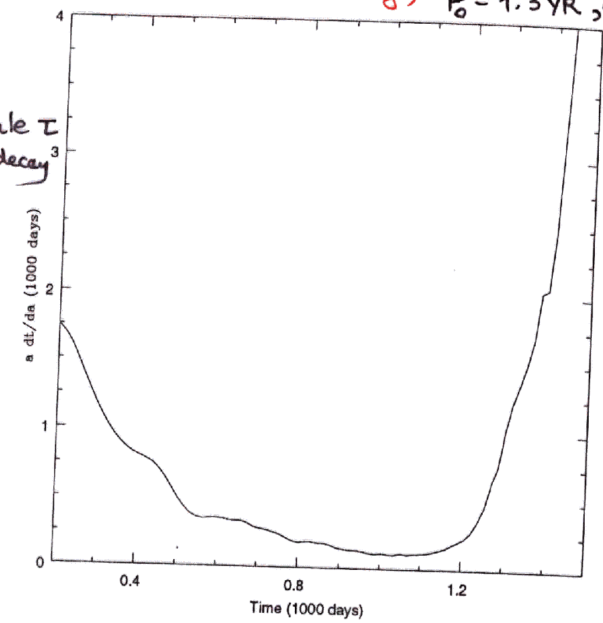
80% of mass ejected in ORB. Plane

They Find $\alpha_{CE} \simeq 0.15$ (⇒ much of Frictional energy release converted into HEAT and

Taam (1995)

16 $M_\odot$ Red Supergiant (Non-Rotating) + 1.4 $M_\odot$ Neutron Star

$P_0 = 1.3$ YR, $a_0 \simeq 3$ AU



The time scale of the orbital decay $(a/\dot{a})$ as a function of time. Both its of 1000 days.

- "Plunge" on timescale ≃ 200^d
- $\tau_{min} = 95^d$
- After ≃ 200^d of heavy frictional energy dissip., core reaches co-Rotation

Ierman et al. (1994)

4.67 $M_\odot$ Red Giant + 0.94 $M_\odot$ dwarf

3 — 3×10^{40} ergs/s

dE/dt (in 10^{40} ergs/s)

2 — 2

1 — 1

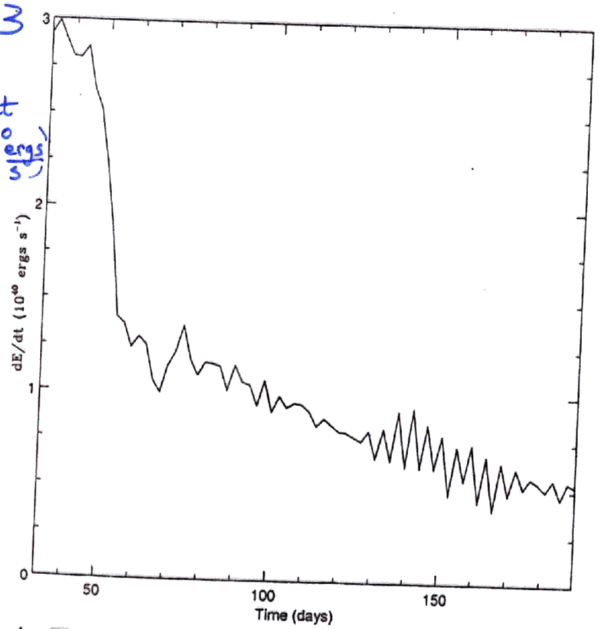


FIG. 4.—The energy dissipation rate deposited in the common envelope by the interaction of the two cores as a function of time. The energy dissipation rate is in units of 10^{40} ergs s^{-1}, and time is measured in days.

"PLUNGE": $L_d \simeq (2-3) \times 10^{40}$ ergs/s for $\approx 50^d$

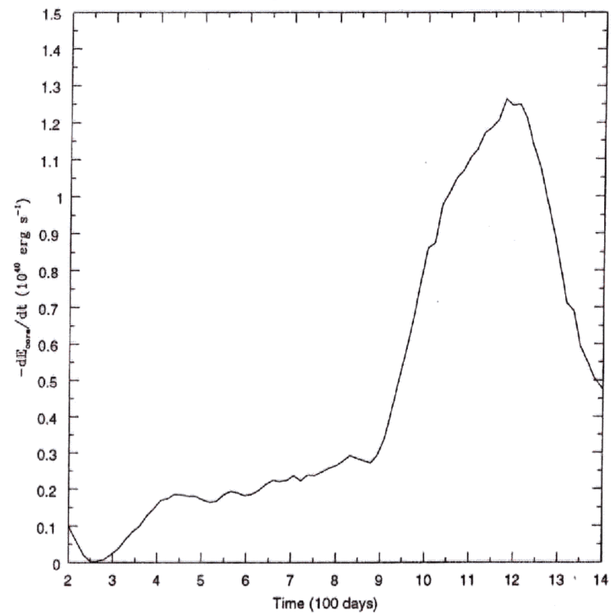
Timescale of Energy-release is typically: $\tau_{dyn} = \tau_{\text{ORBIT companion}}$

In Early Spiral-in : $\tau \simeq 100^d$

Later : $\tau \simeq \tau_{orb}$ (Short)

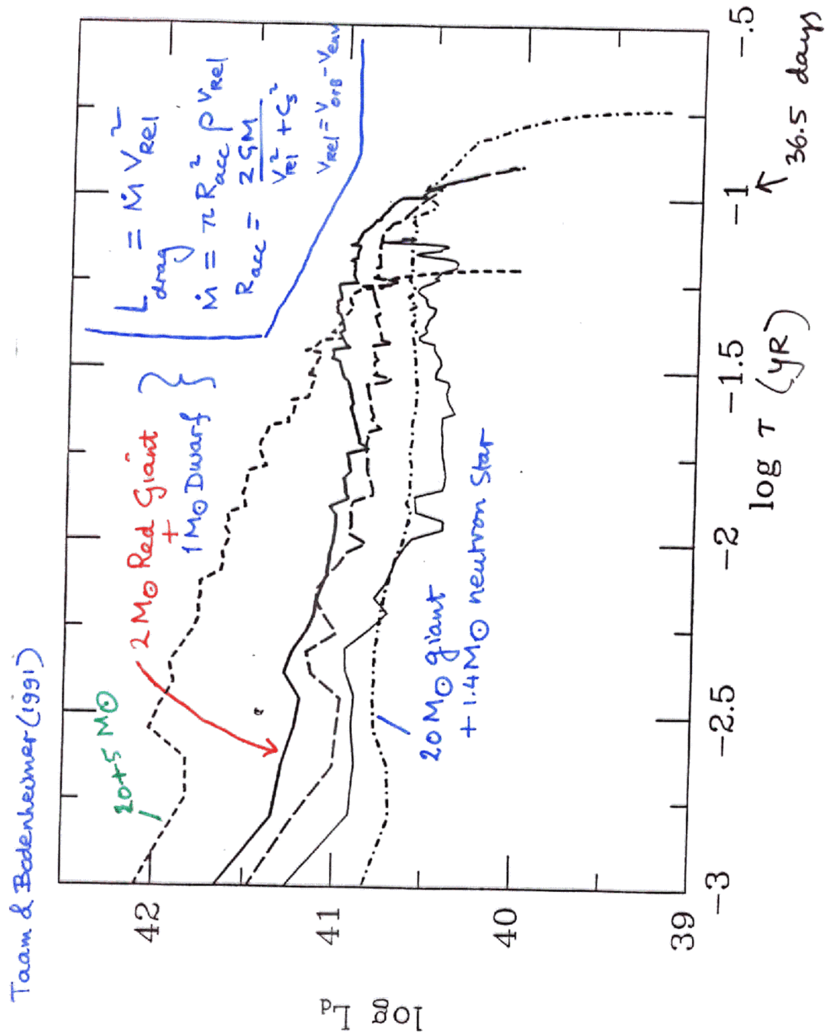
16 $M_\odot$ Red Giant + 1.4 $M_\odot$ Neutron Star (SPH-simul. Taam 1995)

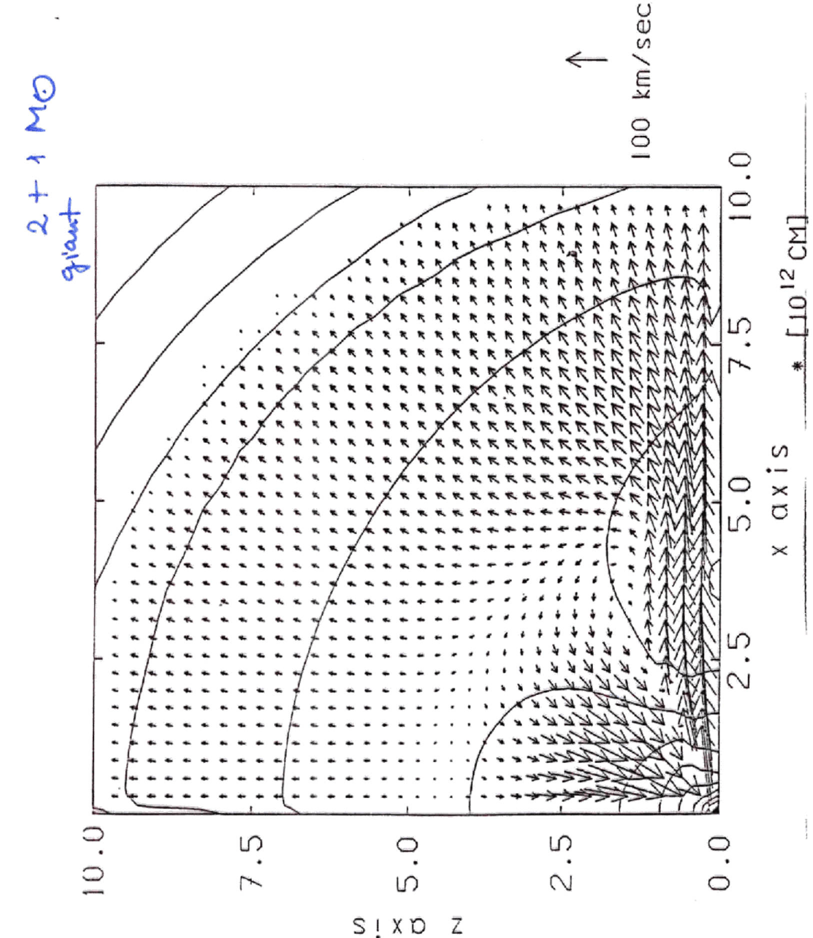
dE/dt (in 10^{40} ergs/s)



$\frac{dE}{dt} \simeq 1.3 \times 10^{40}$ ergs/s for ≈ 50 days

$> 10^{40}$ ergs/s for $\simeq 200$ days


Taam & Bodenheimer (1991)
log L_d
log τ (YR)
36.5 days
2 M⊙ Red Giant + 1 M⊙ Dwarf
20 M⊙ giant + 1.4 M⊙ neutron Star
20+5 M⊙
$L_{drag} = \dot{M} V_{rel}^2$
$\dot{M} = \pi R_{acc}^2 \rho V_{rel}$
$R_{acc} = \frac{2GM}{V_{rel}^2 + C_s^2}$
$V_{rel} = V_{orb} - V_{env}$


2 + 1 M⊙ giant
100 km/sec
x axis [10^{12} CM]
z axis

COMPLETE MERGERS :

1) If star 1 is compact, and final $a_2 < R_{core}$ → complete merger
(e.g.: SHORT-Period HMXBs Like Cen X-3 (P_{orb} = 2.1 days)

2) If star 1 is a Main-seq. Star, but during spiral-in overflows its Roche lobe with respect to M_{core}
↓
STAR 1 dissolves and merges with core &/or envelope of star 2

⇓
- Rapidly Rotating giant
- Ejection of "Ring-like" structures like in SN1987A (MORRIS & Podsiadlowski 2006) 20 $M_\odot$ + 2-5 $M_\odot$ compan.

density enhance-ments in the outflow ←

- Low mass giants (Elliptical Galaxies)

Typical Energy Release Rates "Mergers" (SPIRAL-ins)

$M_2 = 1.2\,M_\odot$, $M_{core} = 0.5\,M_\odot$ } AGB + $M_1 = 0.6\,M_\odot$

Then: $a_2/a_1 \simeq 1/16$ for $\alpha_{CE} = 0.5$

If $a_1 = 0.5$ AU → $a_2 = 6.7\,R_\odot$

and $\Delta E_{released} \simeq \frac{G M_{core} \cdot M_1}{6.7\,R_\odot} \simeq 2 \cdot 10^{47}$ ergs (half of it used for envelope eject.)

$\tau_{spiral-in} \simeq \tau_{dyn} \simeq 2$ months

$L_{peak,\,thermal} \simeq 2 \cdot 10^{40}$ ergs/s for ~ 60^d

! This is, in fact, independent of value of M_1:

If M_1 twice as small ⇒ a_2 twice as small ⇒ $\Delta E_{released}$ is same; τ also same.

- High-mass giants:

$L_{peak} \simeq 10^{41} - 10^{42}$ ergs/s (at most) on similar timescale

Expected Frequency of Events for steady Star Formation Rate and main-sequence compan. mergers.

Assume:

- 25 per cent of stars in binaries with a in range $4 R_\odot$ to 5 AU
- $f(\log a) = \text{const.} = 0.1$ for $\log a\,(\text{AU}) = -1.7$ to 0.7 (-1.7: $4R_\odot$; 0.7: 5 AU)
- $g(q = M_1/M_2) = \text{const.}$ (uncertain!)
- inspiral companions have $q \lesssim 0.25$
- Birthrate $\frac{dN(M)}{dt} = \psi(M) = A \cdot M^{-2.5}$
- Only stars with convective envelopes have dyn.-timescale spiral-in

RESULTING RATES:

- $M_2 \geq 10 M_\odot \Rightarrow R_{\text{mergers}} \simeq 0.02\, R_{SN_{\text{core coll.}}}$
- $M_2 = 4-10 M_\odot$: $R_{\text{mergers}} \simeq 0.08\, R_{SN_{cc}}$
- $M_2 = 1-4 M_\odot$: $R_{\text{mergers}} \simeq R_{SN}$ (Largest contrib. from close to $M_2 \simeq 1$)

(assumed: All stars $\geq 10 M_\odot$ go to core collapse SN).