Binary evolution

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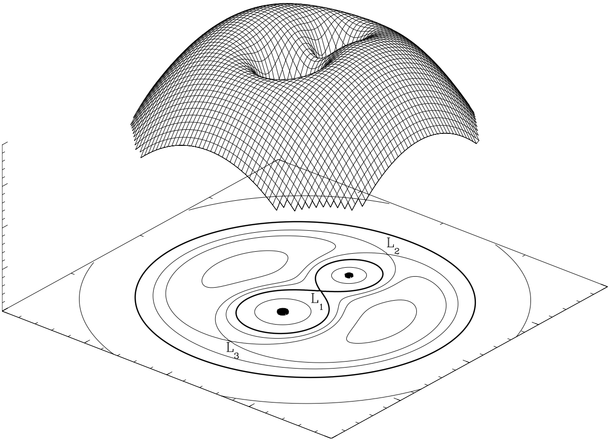
March 13, 2012

Outline of the lecture

- Roche geometry
  - Roche potential
  - Roche lobes
  - Roche-lobe overflow
  - Minimum and maximum periods
- Stable mass transfer
  - Stable conservative MT
  - Stable non-conservative MT
  - Intrinsic drivers of MT
    - nuclear-timescale MT
    - thermal-timescale MT
    - dynamical-timescale MT
  - Extrinsic drivers of MT
    - gravitational waves
    - magnetic braking
  - Eddington limit
- Envelope ejection
  - Common envelope
  - γ envelope ejection
  - Darwin instability
  - Compact binaries and mergers

Roche lobes



$$\frac{R_{\mathrm{Rl},1}}{a} \approx \frac{2}{3^{4/3}} \left(\frac{M_2}{M_{\mathrm{T}}}\right)^{1/3}$$

accurate within 1% (?) for $q_1 < 0.8$ (Paczyński, 1971).

$$\frac{R_{\mathrm{Rl},1}}{a} \approx \frac{0.49\, q_1^{2/3}}{0.6\, q_1^{2/3} + \ln\left(1 + q_1^{1/3}\right)}$$

accurate within 1% for $0 < q_1 < \infty$ (Eggleton, 1983).

Conservative mass transfer

Angular momentum for binary component i in a circular orbit:

$$J_i = |\vec{J}_i| = M_i \left|\vec{v}_i \times \vec{a}_i\right| = M_i v_i a_i = M_i a_i^2 \omega$$

$$J = J_1 + J_2 = \mu a^2 \omega = G^{2/3} \frac{M_1 M_2}{M_{\rm T}^{1/3}} \left(\frac{P}{2\pi}\right)^{1/3}$$

$$\frac{\dot{J}}{J} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{3}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{3}\frac{\dot{P}}{P}$$

Conservative: $\dot{J} = 0, \dot{M}_{\rm T} = 0$:

$$\frac{\dot{P}}{P} = 3\,\dot{M}_1 \frac{M_2 - M_1}{M_1 M_2}$$

Conservative mass transfer

Mass and angular-momentum loss

Non-conservative mass transfer (lose fraction β of transferred mass):

$$\left(\frac{\dot{J}}{J}\right)_{\rm MT} = -\alpha(1-\beta)\frac{M_i}{M_2}\frac{\dot{M}_1}{M_{\rm T}},$$

Gravitational waves (Peters, 1964):

$$\left(\frac{\dot{J}}{J}\right)_{\rm GW} = -\frac{32}{5}\frac{G^{5/3}}{c^5}\left(\frac{2\pi}{P}\right)^{8/3}\frac{M_1 M_2}{M_{\rm T}^{1/3}}$$

Magnetic braking, *e.g.* Verbunt & Zwaan, 1981:

$$\left(\frac{dJ}{dt}\right)_{\rm MB} = -3.8\times 10^{-30} M R^4 \omega^3 \ {\rm dyn\ cm}$$

Magnetic braking, *e.g.* Sills et al., 2000:

$$\begin{aligned}\left(\frac{dJ}{dt}\right)_{\rm MB} &= -K\left(\frac{R}{R_\odot}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{-1/2}\omega^3, \quad \omega \le \omega_{\rm crit} \\ &= -K\left(\frac{R}{R_\odot}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{-1/2}\omega\omega_{\rm crit}^2, \quad \omega > \omega_{\rm crit}\end{aligned}$$

Low-mass X-ray binaries

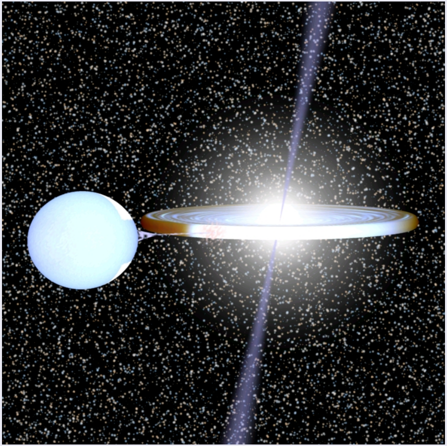
Mechanism

- Low-mass star transfers mass to neutron star or black hole
- Gravitational acceleration causes X-rays:

$$L_x \approx \frac{GM_{ns}}{R_{ns}} \dot{M}_{tr}$$

- Optical radiation comes from reprocessed X-rays in accretion disk

BinSim

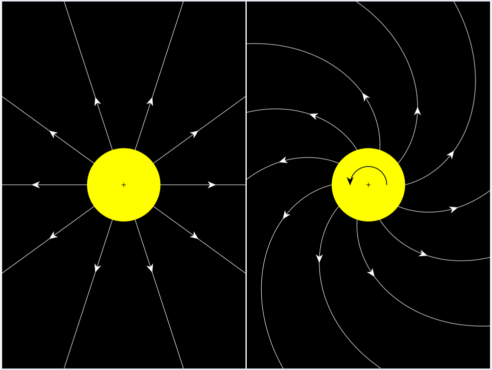


BinSim, R. Hynes, LSU

Magnetic braking

Magnetic wind

- Rotating stars can have magnetic fields
- Evolved stars can have strong winds
- Stellar wind follows magnetic-field lines
- Star loses angular momentum efficiently
- Tidal coupling causes orbit to shrink in case of a binary



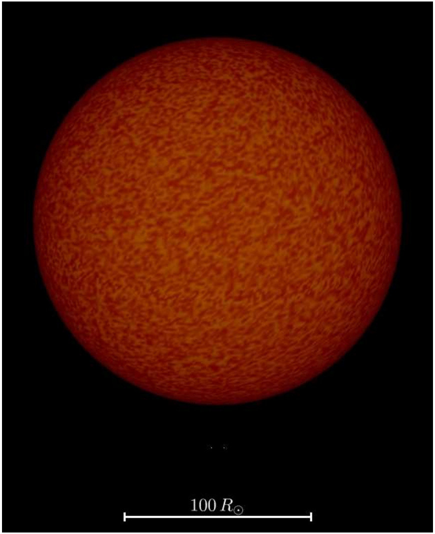
Observed double white dwarfs

System	P_{orb} (d)	a_{orb} ($R_\odot$)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	q_2 (M_2/M_1)	$\Delta\tau$ (Myr)
WD 0135–052	1.556	5.63	0.52 ± 0.05	0.47 ± 0.05	0.90 ± 0.04	350
WD 0136+768	1.407	4.99	0.37	0.47	1.26 ± 0.03	450
WD 0957–666	0.061	0.58	0.32	0.37	1.13 ± 0.02	325
WD 1101+364	0.145	0.99	0.33	0.29	0.87 ± 0.03	215
PG 1115+116	30.09	46.9	0.7	0.7	0.84 ± 0.21	160
WD 1204+450	1.603	5.74	0.52	0.46	0.87 ± 0.03	80
WD 1349+144	2.209	6.59	0.44	0.44	1.26 ± 0.05	—
HE 1414–0848	0.518	2.93	0.55 ± 0.03	0.71 ± 0.03	1.28 ± 0.03	200
WD 1704+481a	0.145	1.14	0.56 ± 0.07	0.39 ± 0.05	0.70 ± 0.03	-20[a]
HE 2209–1444	0.277	1.88	0.58 ± 0.08	0.58 ± 0.03	1.00 ± 0.12	500

[a] Unclear which white dwarf is older

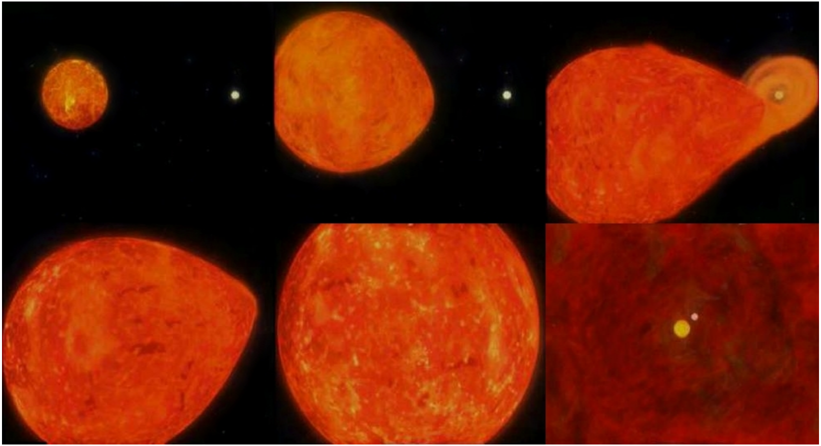
See references in: Maxted et al., 2002 and Nelemans & Tout, 2005.

Common envelope



- Average orbital separation:
  - 7 $R_\odot$
- Typical progenitor:
  - $M_c \gtrsim 0.3\, M_\odot$
  - $R_* \sim 100\, R_\odot$

Common envelope



Envelope ejection

Common envelope with energy conservation (spiral-in)

$$U_{\rm bind} = \alpha_{\rm CE} \left[\frac{G\,M_{\rm 1f}\,M_2}{2\,a_{\rm f}} - \frac{G\,M_{\rm 1i}\,M_2}{2\,a_{\rm i}} \right] \qquad (0 < \alpha_{\rm CE} \le 1)$$

(Paczynski, 1976; Webbink, 1984)

Envelope ejection with AM conservation (spiral-in not necessary)

- Average specific angular momentum of the system (Nelemans et al., 2000):

$$\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} = \gamma_{\rm s} \frac{M_{\rm 1i} - M_{\rm 1f}}{M_{\rm tot,i}} \qquad (\gamma_{\rm s} \sim 1.5)$$

- Specific angular momentum of the donor (van der Sluys et al., 2006):

$$\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} = \gamma_{\rm d} \frac{M_{\rm 1i} - M_{\rm 1f}}{M_{\rm tot,f}} \frac{M_{\rm 2i}}{M_{\rm 1i}} \qquad (\gamma_{\rm d} \sim 1)$$

- Specific angular momentum of the accretor (van der Sluys et al., 2006):

$$\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} = \gamma_{\rm a} \left[1 - \frac{M_{\rm tot,i}}{M_{\rm tot,f}} \exp\left(\frac{M_{\rm 1f} - M_{\rm 1i}}{M_2} \right) \right] \qquad (\gamma_{\rm a} \sim 1)$$

Envelope ejection

Assumption:

- Common envelopes and envelope ejections occur much faster than nuclear evolution, hence:
  - core mass does not grow during envelope ejection
  - no accretion by companion during envelope ejection

Online material

http://www.astro.ru.nl/∼sluys/

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