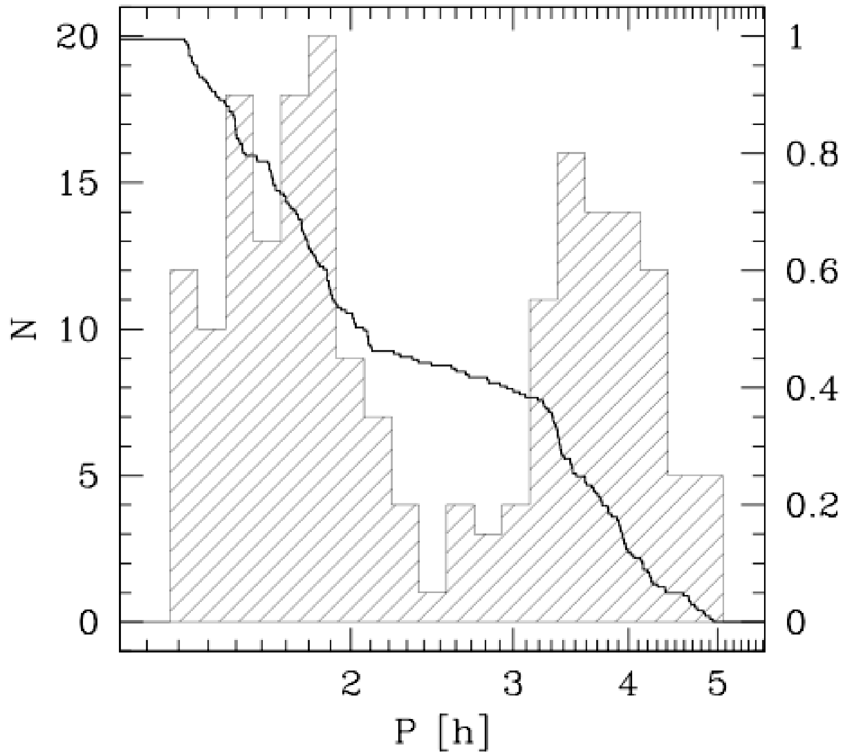
Cataclysmic Variables

- mass transfer from low-mass dwarf ($\lesssim 1.4\,M_\odot$) to white dwarf (cf. supersoft sources, symbiotic binaries)
- mass transfer mainly driven by magnetic braking and gravitational radiation
- period gap between 2 and 3 hr

disrupted magnetic braking model (Rappaport et al. 1983; Spruit & Ritter 1983)

- ▷ magnetic braking stops when the donor becomes fully convective (no dynamo?)
- ▷ system becomes temporarily detached at $P_{orb} = 3$ hr
- ▷ gravitational radiation brings the system back into contact at 2 hr

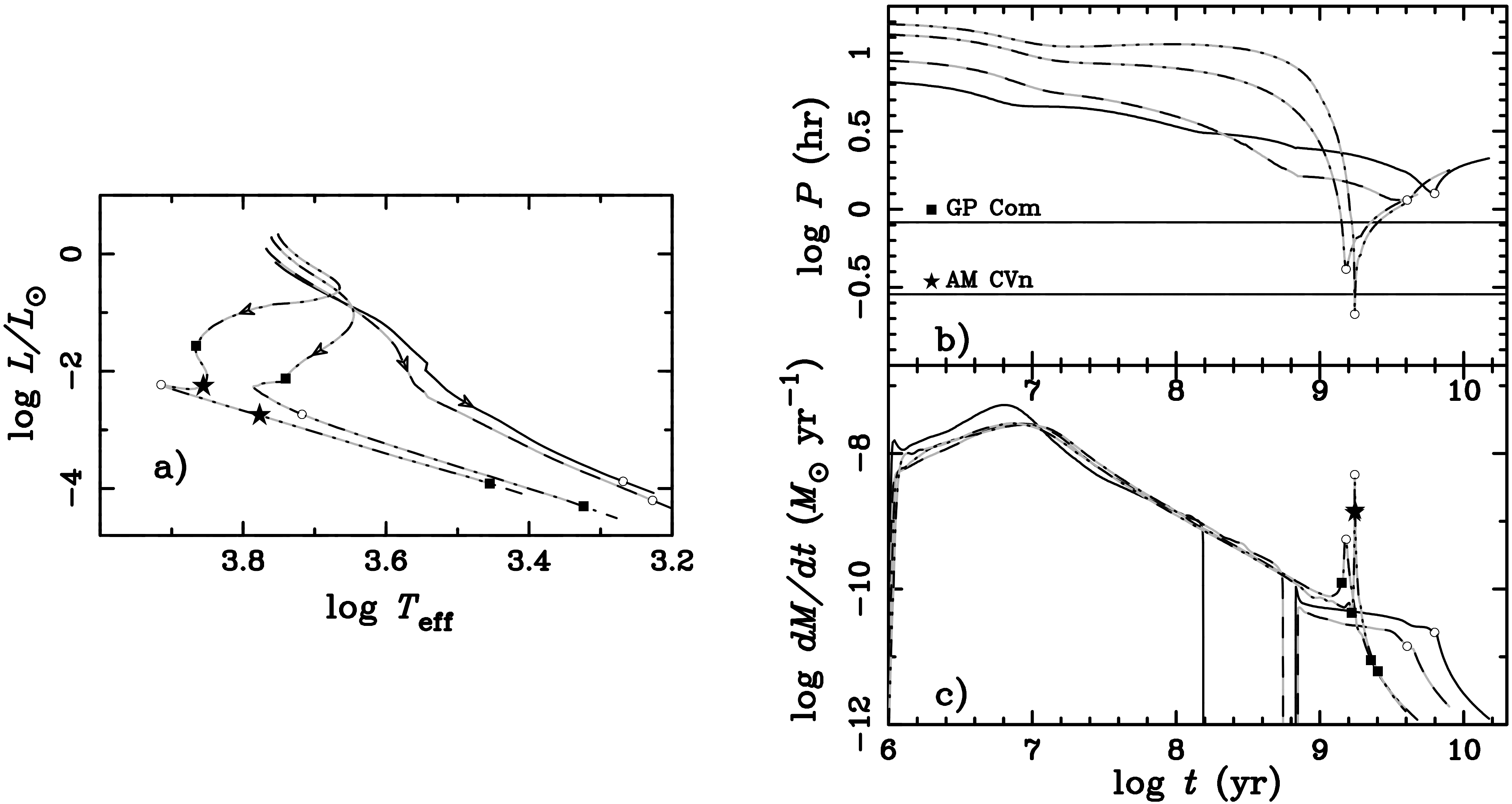


(Kolb et al.)

- period minimum at $P_{orb} = 75$ min, when donor stop H burning and becomes degenerate

Open Issues

- magnetic braking law
- magnetic activity observed in late M dwarfs



log $L/L_\odot$
log T_{eff}
a)
b)
c)
log P (hr)
GP Com
AM CVn
log dM/dt ($M_\odot$ yr^{-1})
log t (yr)

AM CVn Stars

- systems with initially slightly evolved donors evolve below the classical period minimum (shorter/no period gap)

→ gradual conversion into He white dwarf

→ orbital periods as short as 7 min

→ CV channel for AM CVn stars

  ▷ may dominate at the long-period end of AM CVn systems (signature: hydrogen)

- short-period AM CVn's (no hydrogen)

  ▷ He White Dwarf donor or

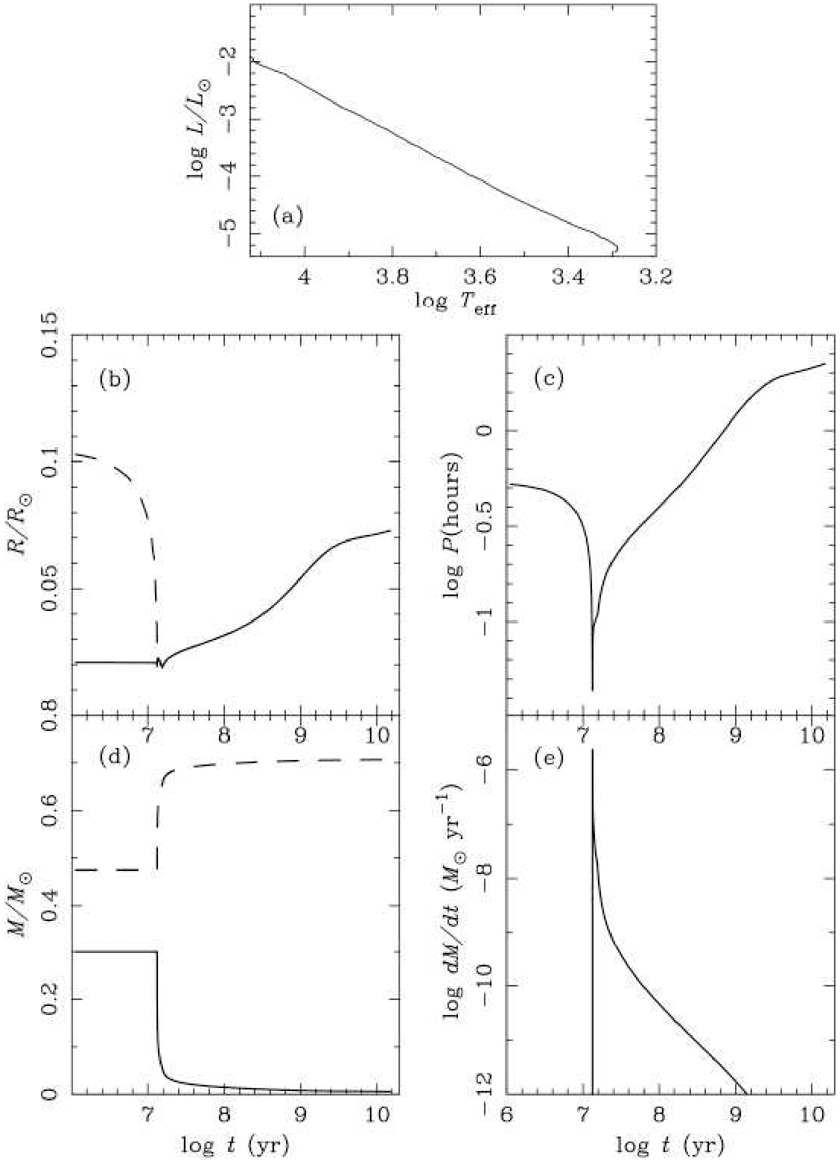
  ▷ helium-star donor (burning He initially)

- the future of α Leo (Regulus)

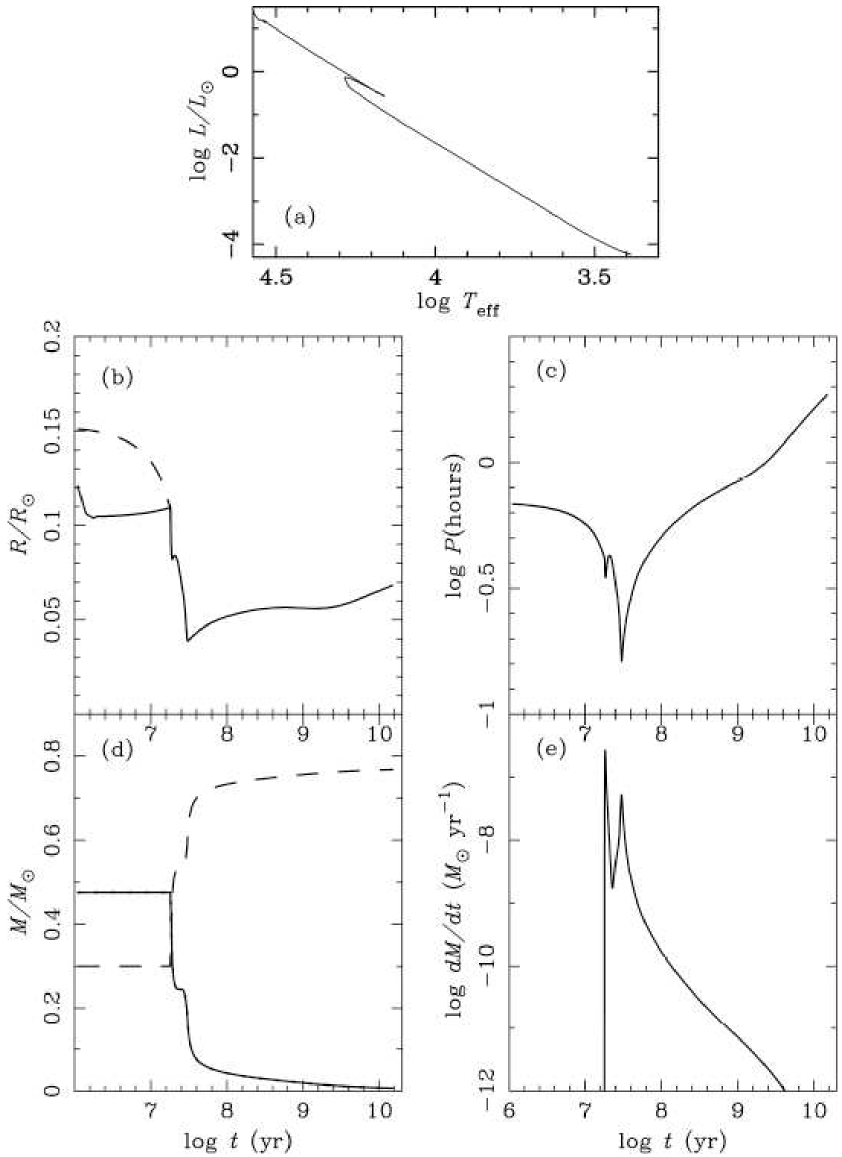
  ▷ Gies et al. (2008): WD companion with $P_{\rm orb} = 40.1\,$d

  ▷ explains rapid rotation, etc.

The Future of Regulus (Rappaport, Podsiadlowski & Horev 2009)



He WD Channel

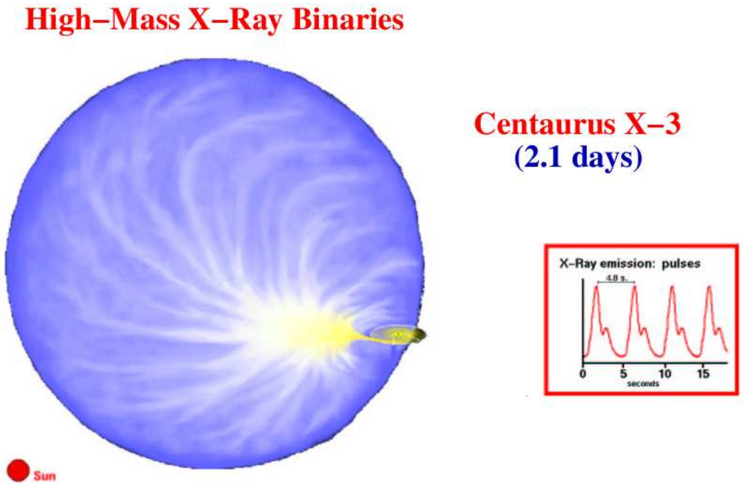


Helium-Star Channel

X-Ray Binaries

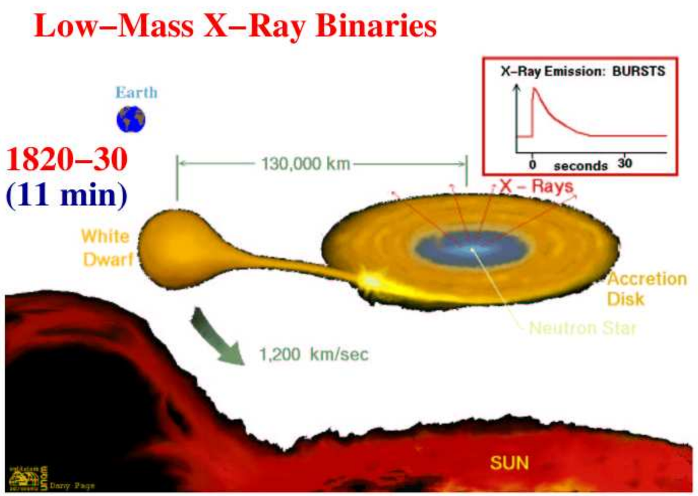
Basic Properties

- **generic system:** a Roche-lobe filling star (low-mass, massive, white dwarf) transfers matter to a compact companion (neutron star, black hole, [white dwarf])
- ***traditionally*** **two main classes:** high-mass X-ray binaries (HMXBs; $M_2 \gtrsim 10\,M_\odot$) and low-mass X-ray binaries (LMXBs; $M_2 \lesssim 1.5\,M_\odot$)
  - ▷ missing intermediate-mass systems?
  - ▷ **probably not:** most systems classified as LMXBs almost certainly originate from intermediate-mass X-ray binaries (IMXBs, $1.5\,M_\odot \lesssim M_2 \lesssim 5\,M_\odot$), but have already lost most/transferred most of their mass



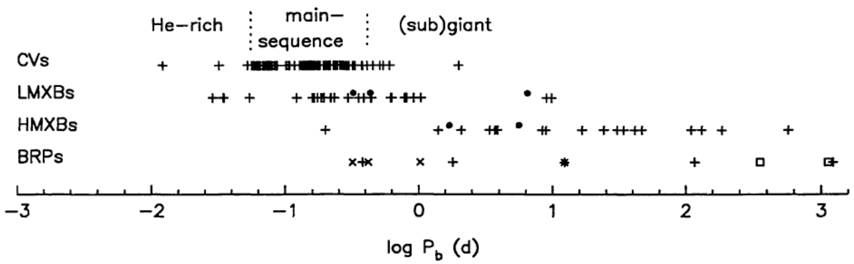
High-Mass X-Ray Binaries

- relatively hard X-ray spectra: $kT \gtrsim 15\,keV$
- type of variability: regular X-ray pulsations; no X-ray bursts
- concentrated towards the Galactic plane, young age $\lesssim 10^7\,yr$
- optical counterparts: O, B stars with $L_{opt}/L_X > 1$



Orbital Period Distributions

- known periods only! Selection effects!

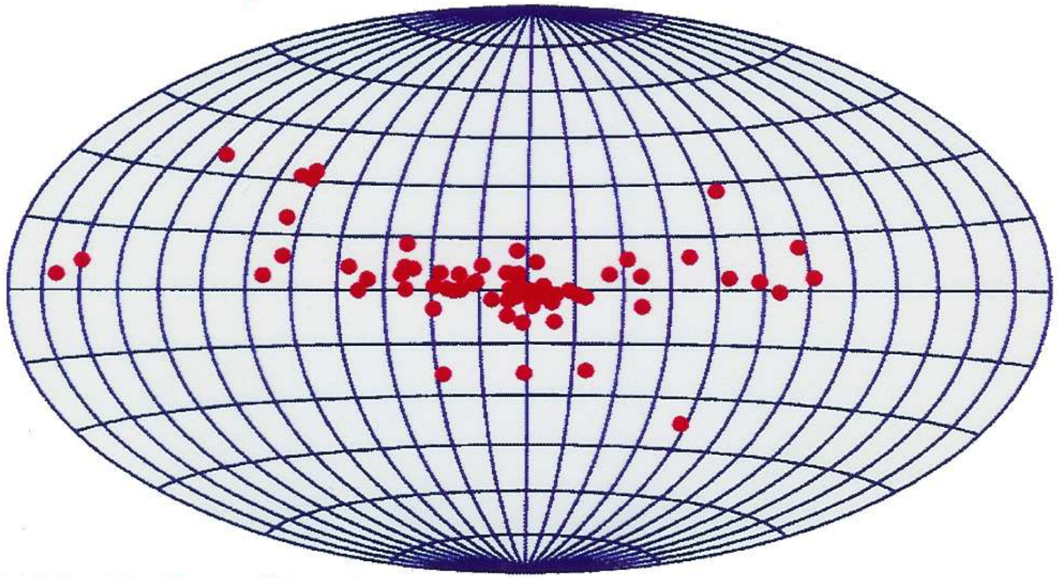


Low-Mass X-Ray Binaries

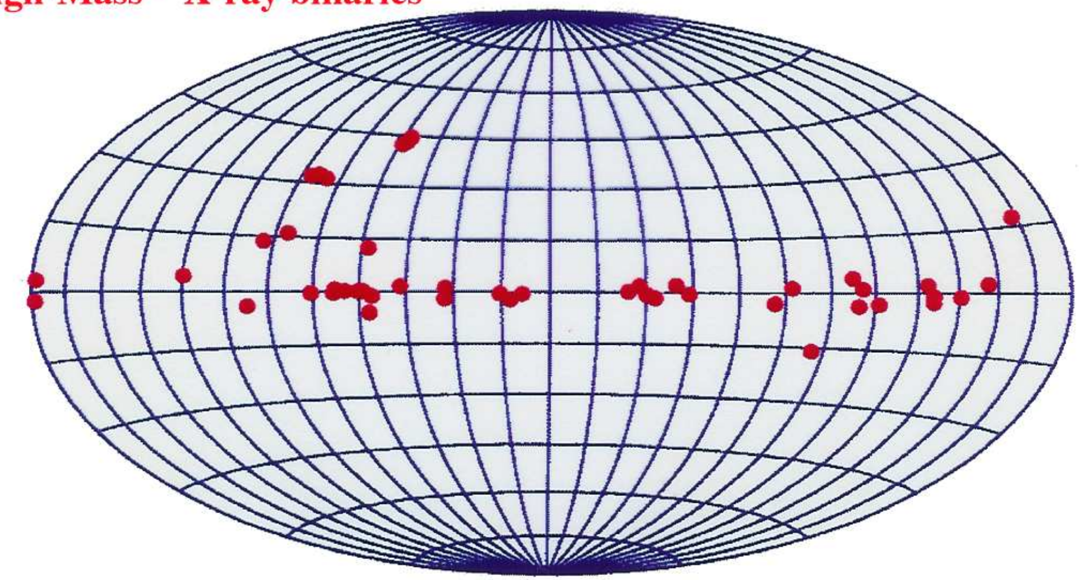
- softer X-ray spectra: ($kT \lesssim 15\,keV$)
- type of variability: often X-ray bursts, sometimes pulsations (recent: ms pulsations!)
- not so concentrated to the Galactic plane; older?
- faint optical counterparts: $L_{opt}/L_X < 0.1$ (usually undetectable!)

Galactic Distribution of X-ray binaries

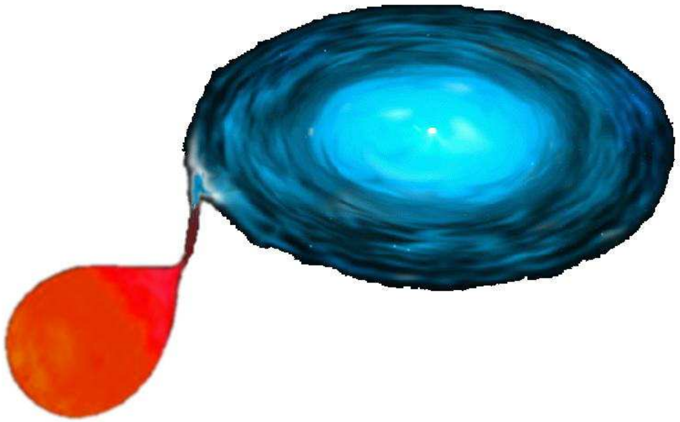
"Low-Mass" X-ray binaries



"High-Mass" X-ray binaries



Low-Mass X-Ray Binaries



- neutron-star (black-hole) binaries with orbital periods of typically hours to less than a few days (for those $\sim 30\,\%$ with known periods)
- the companion stars are "believed" to be low-mass objects:

  $P < 1\,\mathrm{hr}$: degenerate stars ($M_2 \lesssim 0.1\,M_\odot$)

  $3\,\mathrm{hr} < P \lesssim 10\,\mathrm{hr}$: main-sequence stars

  $P \gtrsim 10\,\mathrm{hr}$: subgiants, giants (?)

- they are concentrated in the direction of the Galactic center ("Bulge Sources") and in globular clusters (old population?)

  BUT: neutron stars receive a kick at birth (median: $200 - 250\,\mathrm{km/s}$)

  → LMXBs receive a kick of $180 \pm 80\,\mathrm{km\,s^{-1}}$ (Brandt and Podsiadlowski 1994/95)

  → the LMXB distribution is consistent with a young progenitor population

Formation Scenarios

- the present size of many XRB's $(\sim 0.1 - 10\,R_\odot)$ is much smaller than the size of a blue/red supergiant, the progenitor of the compact object

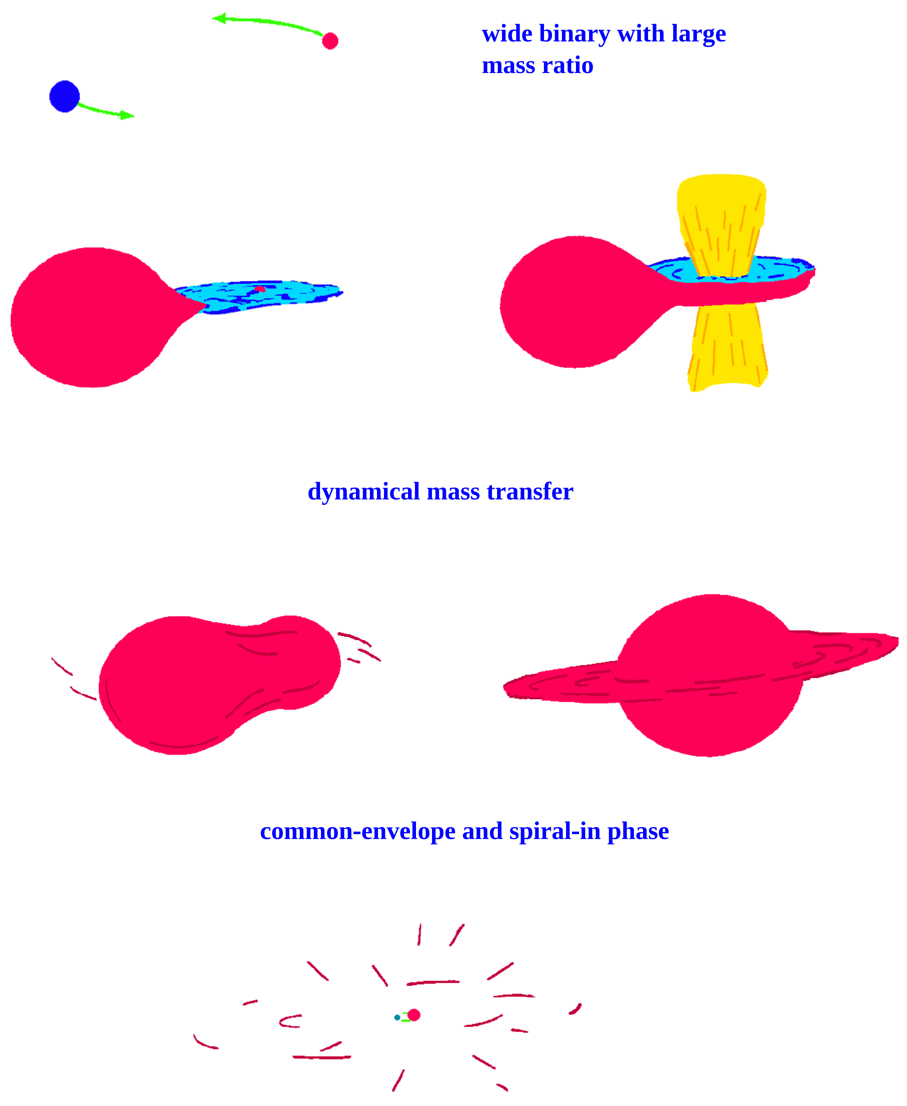
  $\rightarrow$ require drastic shrinkage of orbit

- common-envelope evolution

  ▷ mass transfer for supergiant is often unstable (star expands when losing mass rapidly; Roche lobe shrinks) $\rightarrow$ companion star cannot accrete all the transferred matter and is engulfed $\rightarrow$ formation of a common envelope (CE) $\rightarrow$ friction $\rightarrow$ spiral-in

  ▷ CE is ejected when $\alpha_{\rm CE}\,\Delta E_{\rm orb} > E_{\rm bind}$, where $\Delta E_{\rm orb}$ is the orbital energy released, $E_{\rm bind}$ the binding energy of the envelope and $\alpha_{\rm CE}$ a generally poorly determined efficiency factor

Formation of Low-Mass X-Ray Binaries (I)



ejection of common envelope and subsequent supernova

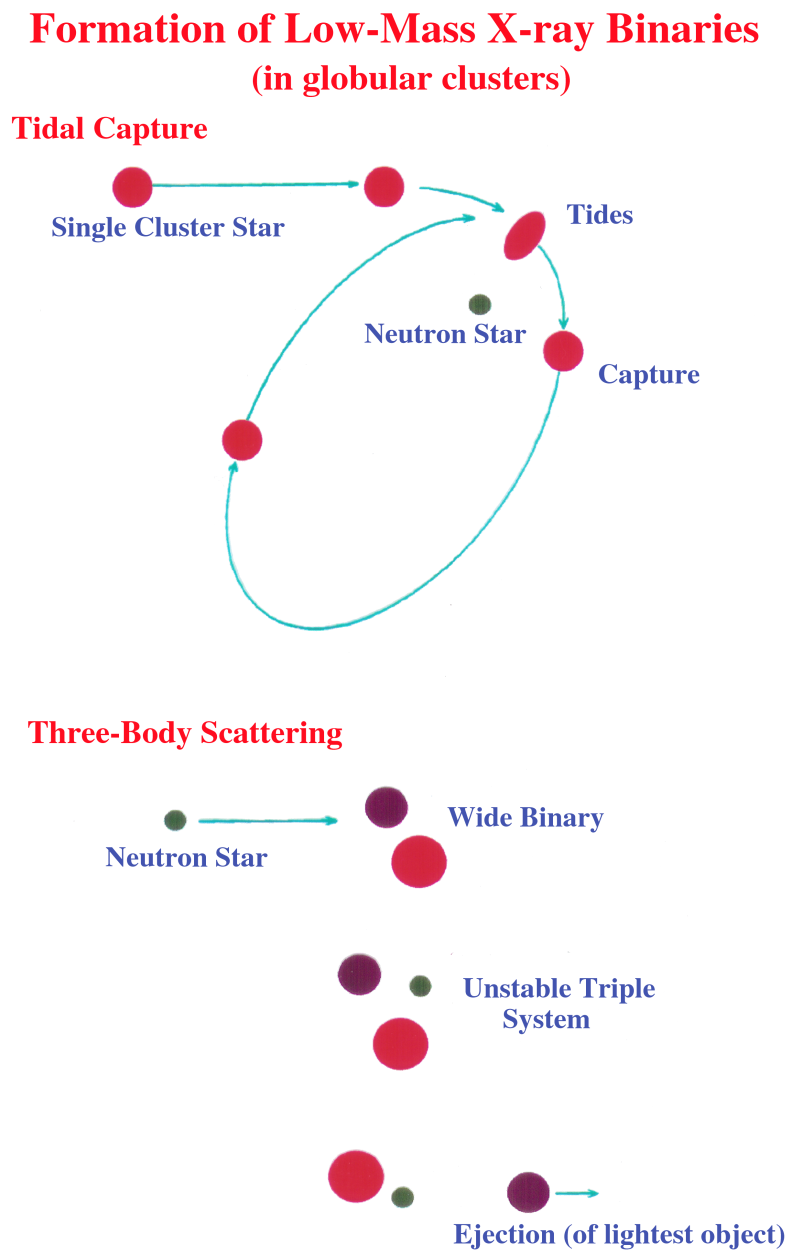
- LMXBs are more frequent in globular clusters (GCs)
  - ▷ Galaxy: ∼ 100; GCs: ∼ 10 LMXBs

but: globular clusters only contain 0.05 % of the mass of the Galaxy

→ 20 times more frequent

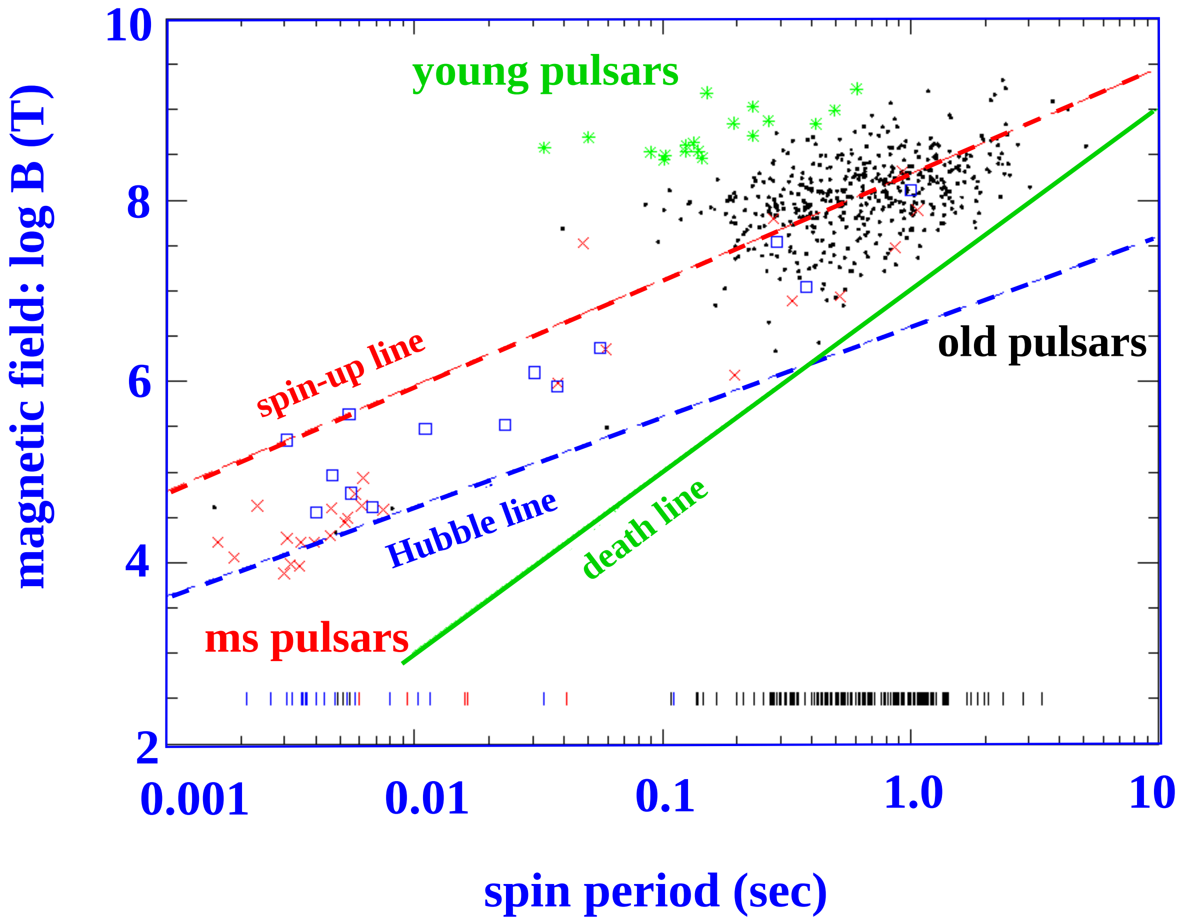
→ different formation mechanisms

  - ▷ tidal capture, three-body interactions in GCs



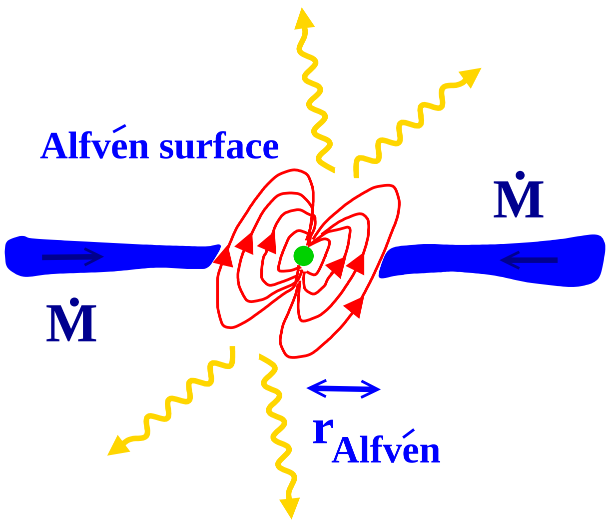
L/IMXBs are the progenitors of the majority of millisecond pulsars

Radio Pulsars: the P-B Diagram



MILLISECOND (RECYCLED) PULSARS

- a group of $\sim$ 200 radio pulsars with very short spin periods (shortest: 1.4 ms) and relatively weak magnetic fields ($B \lesssim 10^6$ T)
- they are preferentially members of binary systems,
- they have spin-down timescales comparable or longer than the Hubble time (age of the Universe)
- standard model
  - ▷ these pulsars are neutron stars in binary systems that spin-down first, lose their strong magnetic field (due to accretion?)
  - ▷ and are spun-up by accretion from a companion

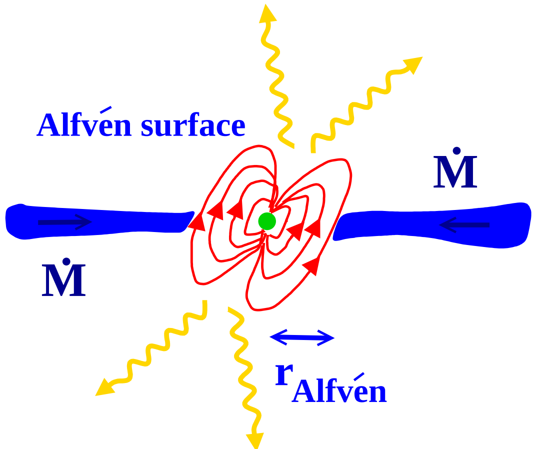


- magnetospheric accretion: magnetic field becomes dominant when magnetic pressure > ram pressure in flow → flow follows magnetic field lines (below r_A)
- spin-up due to accretion of angular momentum
- equilibrium spin period: $v_{rot}(r_A) = v_{Kepler}(r_A)$

$\rightarrow$

$$P_{eq} = \simeq 2\,\text{ms}\,\left(B/10^5\,\text{T}\right)^{6/7}\,\left(\dot{M}/\dot{M}_{Edd}\right)^{-3/7}$$

Neutron Star Spin-up by Accretion



- when magnetic fields are important, the accretion flow near the neutron star becomes dominant and channels the mass towards the poles, making the object a X-ray pulsar
- Alfvén radius: where kinetic energy $\sim$ magnetic energy density,i.e. $\frac{1}{2}\rho v^2 \simeq \frac{B(r)^2}{2\mu_0}$
- approximating the flow velocity v by the free-fall velocity, i.e. $v \simeq v_{ff} = \left(\frac{2GM_{NS}}{R_{Alf}}\right)^{1/2}$,
- obtaining the density ρ from mass conservation (quasi-spherical flow) $\rho \simeq \frac{\dot{M}}{4\pi R_{Alf}^2 v_{ff}}$
- and assuming a dipole magnetic field $(B \propto r^{-3})$ $B(r) \sim \frac{B_0 R_{NS}^3}{R_{Alf}^3}$ (where B_0 is the surface field strength)

$\rightarrow$

$$R_{Alf} \simeq 2.9 \times 10^4\,\mathrm{m} \left(\frac{B}{10^5\,\mathrm{T}}\right)^{4/7} \left(\frac{\dot{M}}{2 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{-2/7}$$

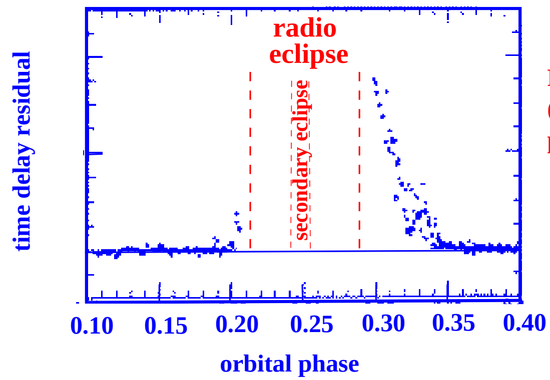
- equilibrium spin period (spin-up line!): $P_{spin} \sim$ orbital period at $R_{Alf} = 2\pi\sqrt{R_{Alf}^3/GM_{NS}}$

$\rightarrow$

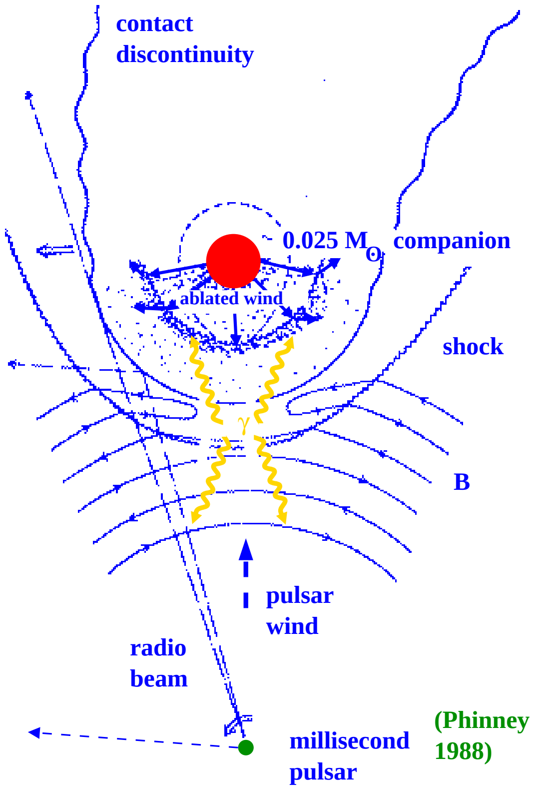
$$P_{eq} \simeq 2.3\,\mathrm{ms} \left(\frac{B}{10^5\,\mathrm{T}}\right)^{6/7} \left(\frac{\dot{M}}{2 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{-3/7}$$

- a significant fraction of millisecond pulsars are single
  - → pulsar radiation has evaporated the companion
    - ▷ example: PSR 1957+20 (the black-widow pulsar): companion mass: only $0.025\,M_\odot$
    - ▷ direct evidence for an evaporative wind from the radio eclipse (much larger than the secondary)
  - → comet-like evaporative tail

(Fruchter, Stinebring, Taylor 1988)



PSR 1957+20 (black-widow pulsar)



(Phinney et al. 1988)

LMXB Evolution

- XRBs with low-mass donors

→ evolution similar to CVs

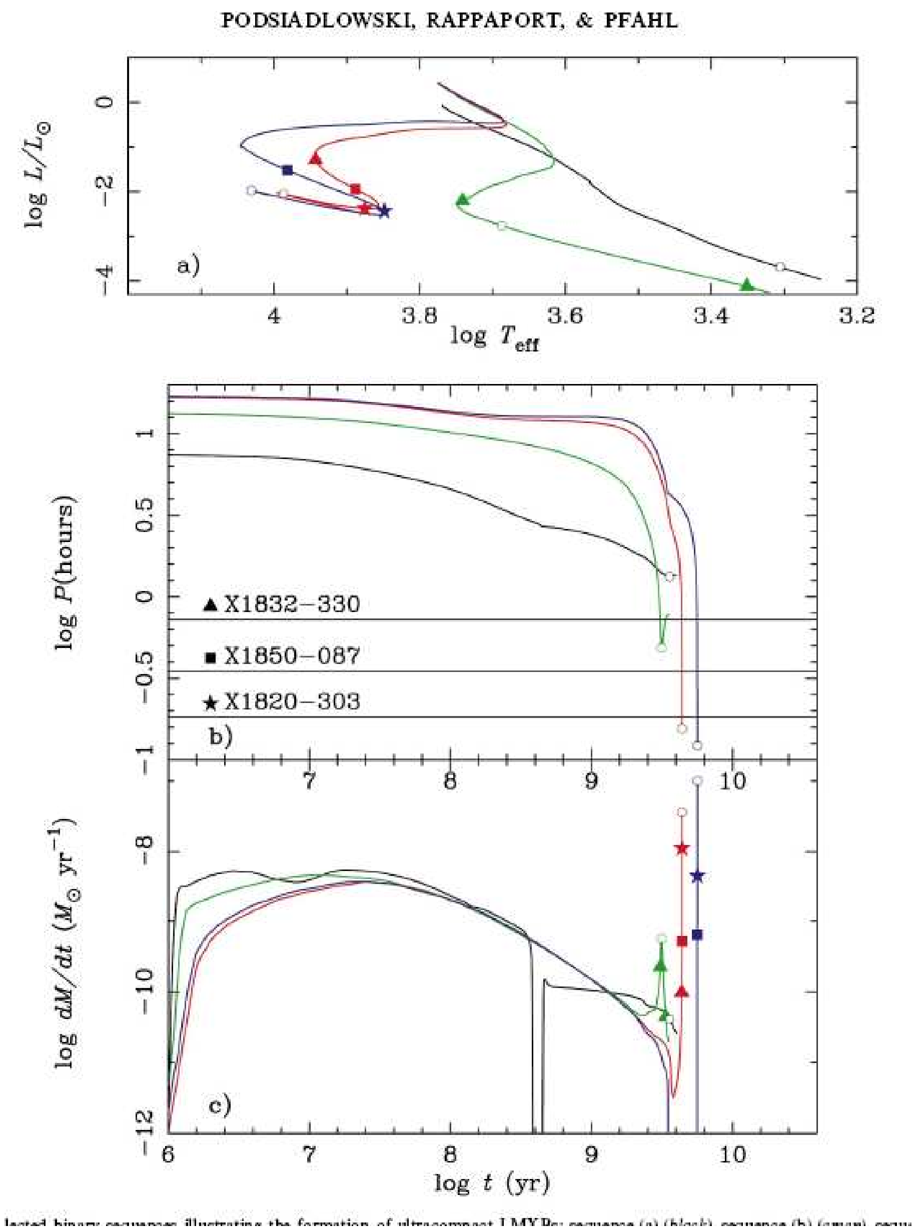
▷ mass transfer dominated by magnetic braking and gravitational radiation

but: no extended period gap or sharp minimum period

▷ evolved donors (below "bifurcation period")

→ ultracompact binaries (P $\simeq$ 10 min; similar to AM CVns) (note: most ultracompacts probably have WD companions)

▷ the mass-transfer rate is relatively low for most of the X-ray phase



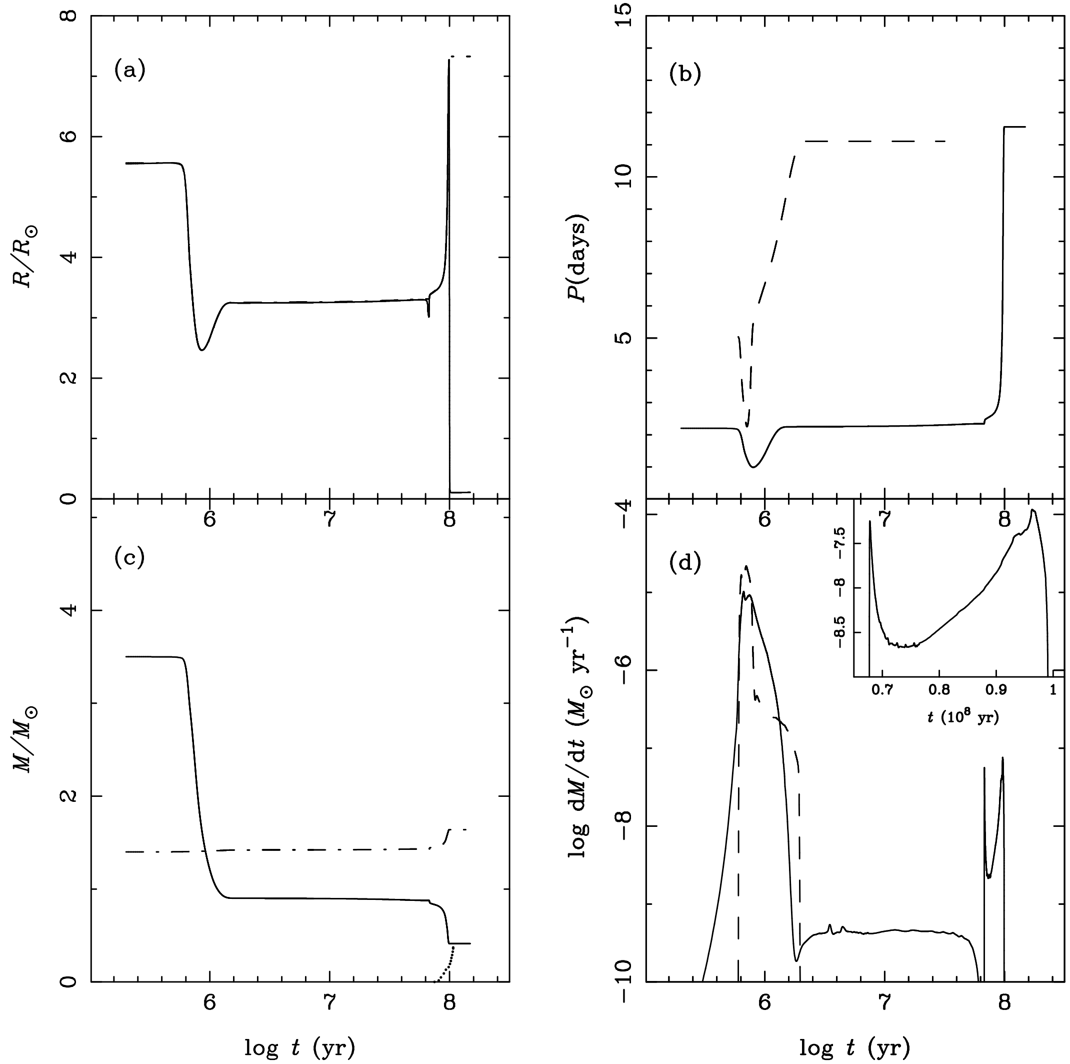
The Role of Intermediate-Mass X-Ray Binaries (IMXB)

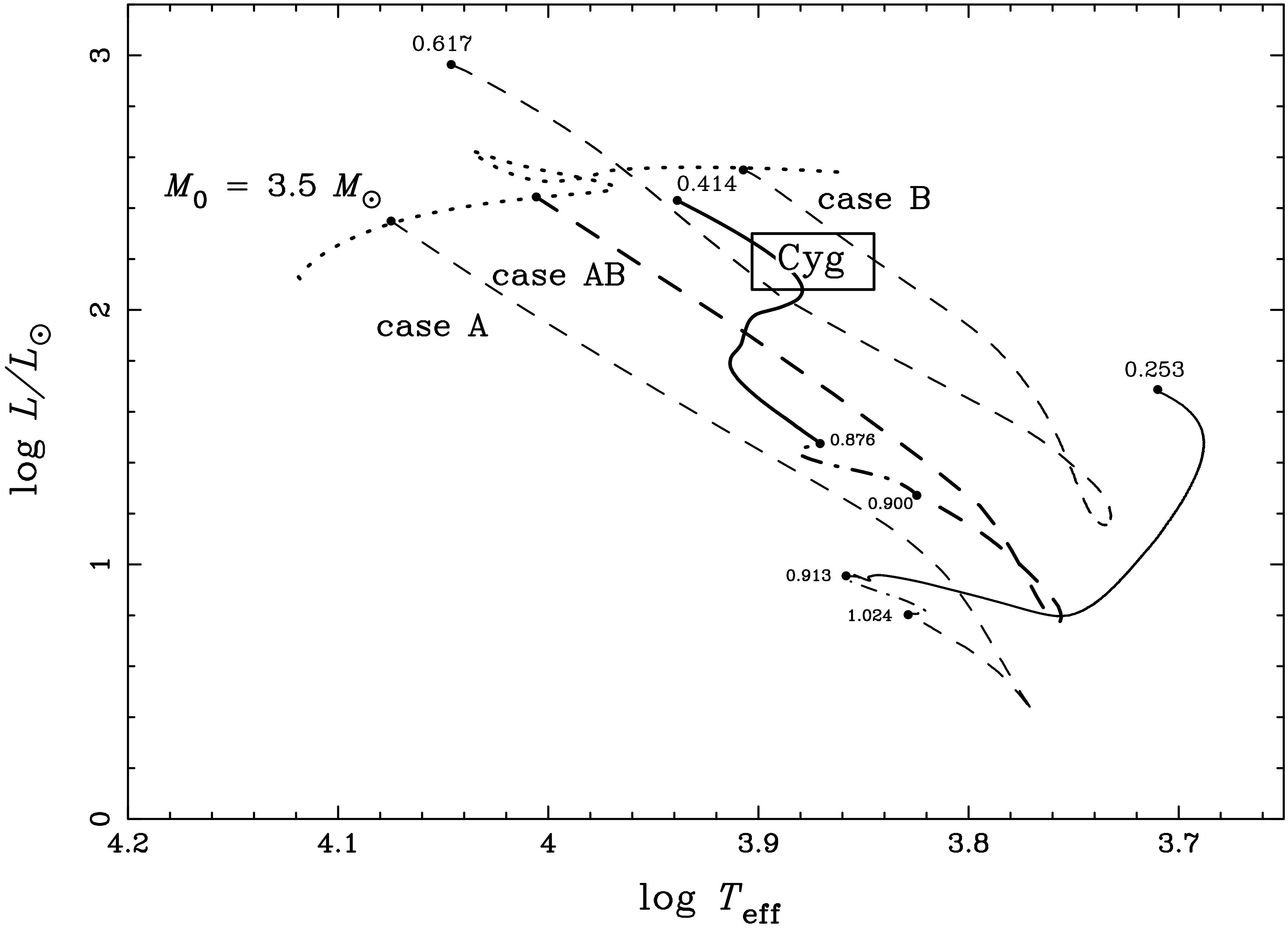
The Case of Cygnus X-2 ($P_{orb} \simeq 10\,d$)

- Casares et al. (1998): donor is A9 III star ($\simeq 7400\,K$)

$\longrightarrow$ requires an initially intermediate-mass star ($\simeq 3.5\,M_\odot$) that started mass transfer near the end of or just after the main sequence (King & Ritter; Podsiadlowski & Rappaport)

- initial thermal timescale mass transfer
  - ▷ maximum $\dot{M} \sim 10^{-5}\,M_\odot\,yr^{-1}$
  - ▷ must be lost from the system ($\dot{M}_{edd} \simeq 10^{-8}\,M_\odot\,yr^{-1}$)
- Do IMXBs dominate the XRB population?





0.617
$M_0 = 3.5\ M_\odot$
0.414
case B
Cyg
case AB
case A
0.253
0.876
0.900
0.913
1.024
log $L/L_\odot$
log $T_{\rm eff}$
0
1
2
3
4.2
4.1
4
3.9
3.8
3.7

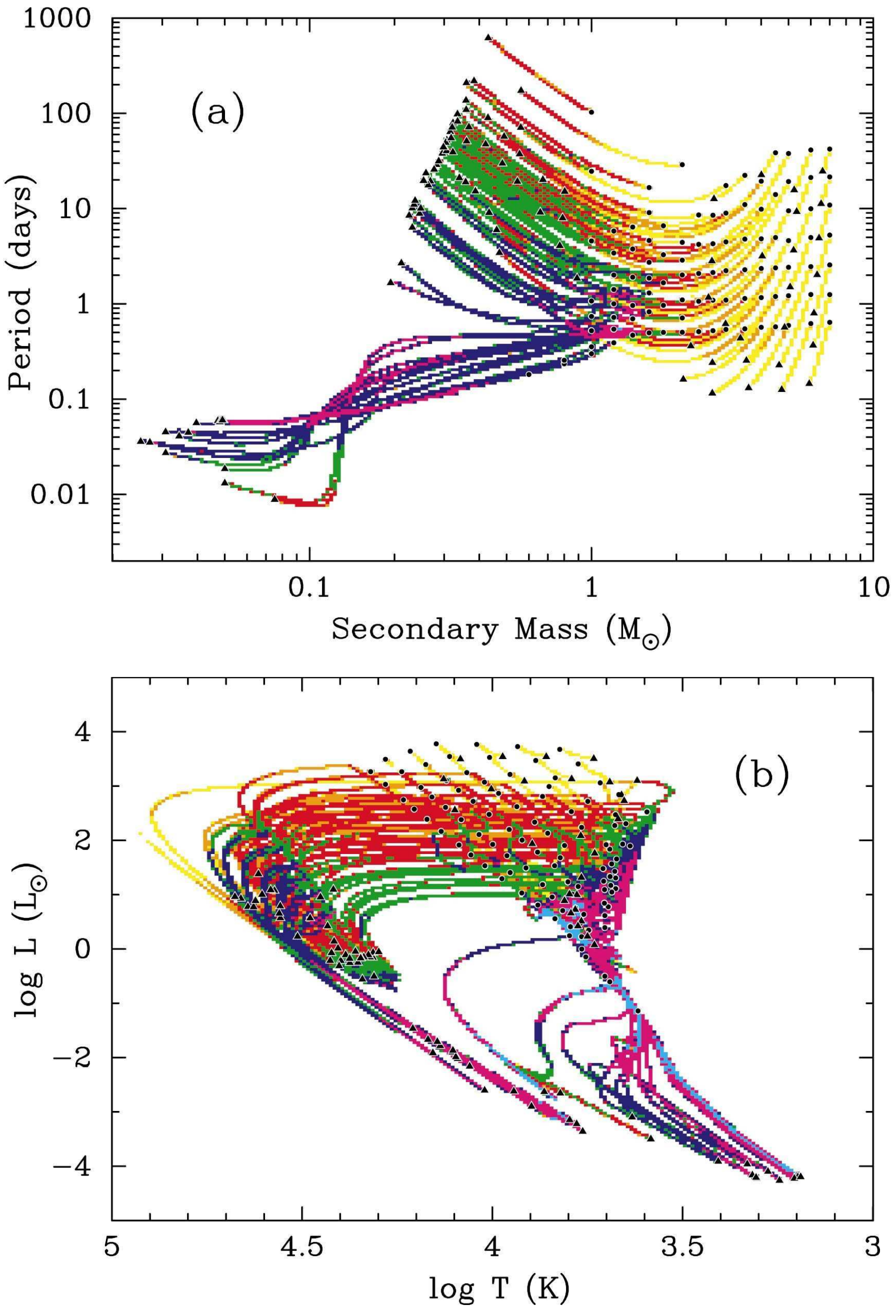


FIG. 2.—Time-weighted evolutionary tracks for the 100 binary sequences in (*a*) the secondary mass–orbital period plane and (*b*) the secondaries in the H-R diagram. The color of the tracks indicates how much time systems spend in a particular rectangular pixel in the diagrams (from short to long: yellow, orange, red, green, blue, magenta, cyan). The minimum time displayed was chosen to be 100 yr, and the maximum time in each of the panels is $\sim$9.5 Gyr. The seven colors are distributed evenly in log *t* between these times. Circles and triangles mark the starting and final points in the sequences, respectively.

The I/LMXB Population

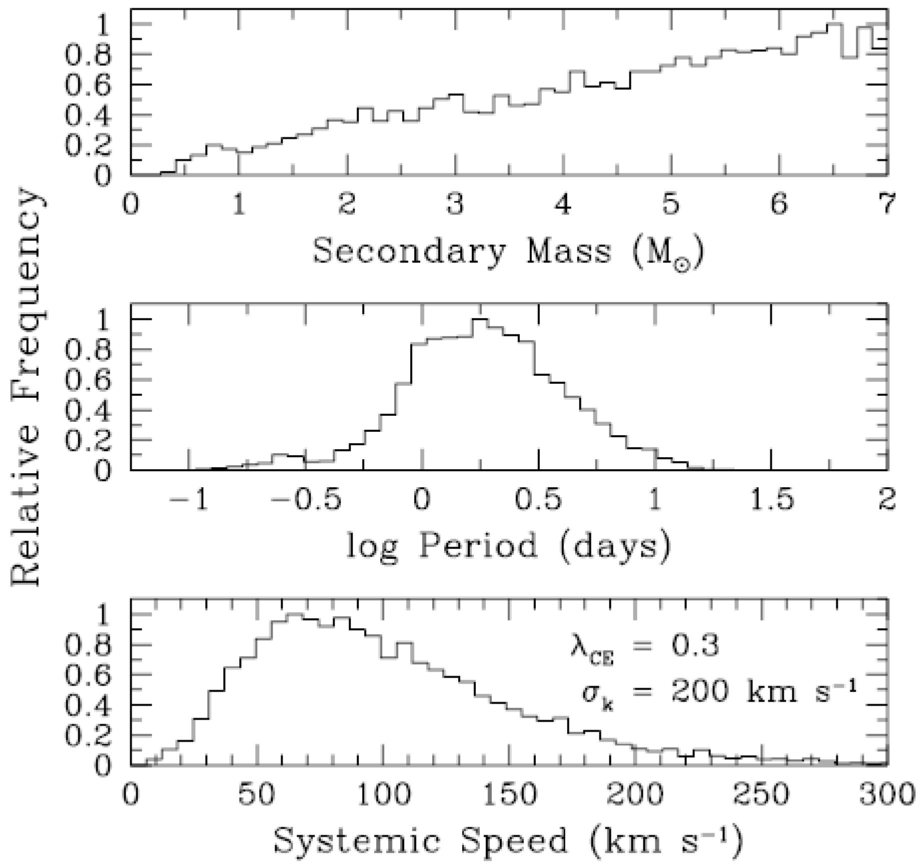
binary population synthesis: using realistic binary evolution calculations (Pfahl et al. 2003)

- ▷ initial distribution dominated by intermediate-mass stars (systems easier to form!)
- ▷ present distribution dominated by low-mass donors (lifetime!)

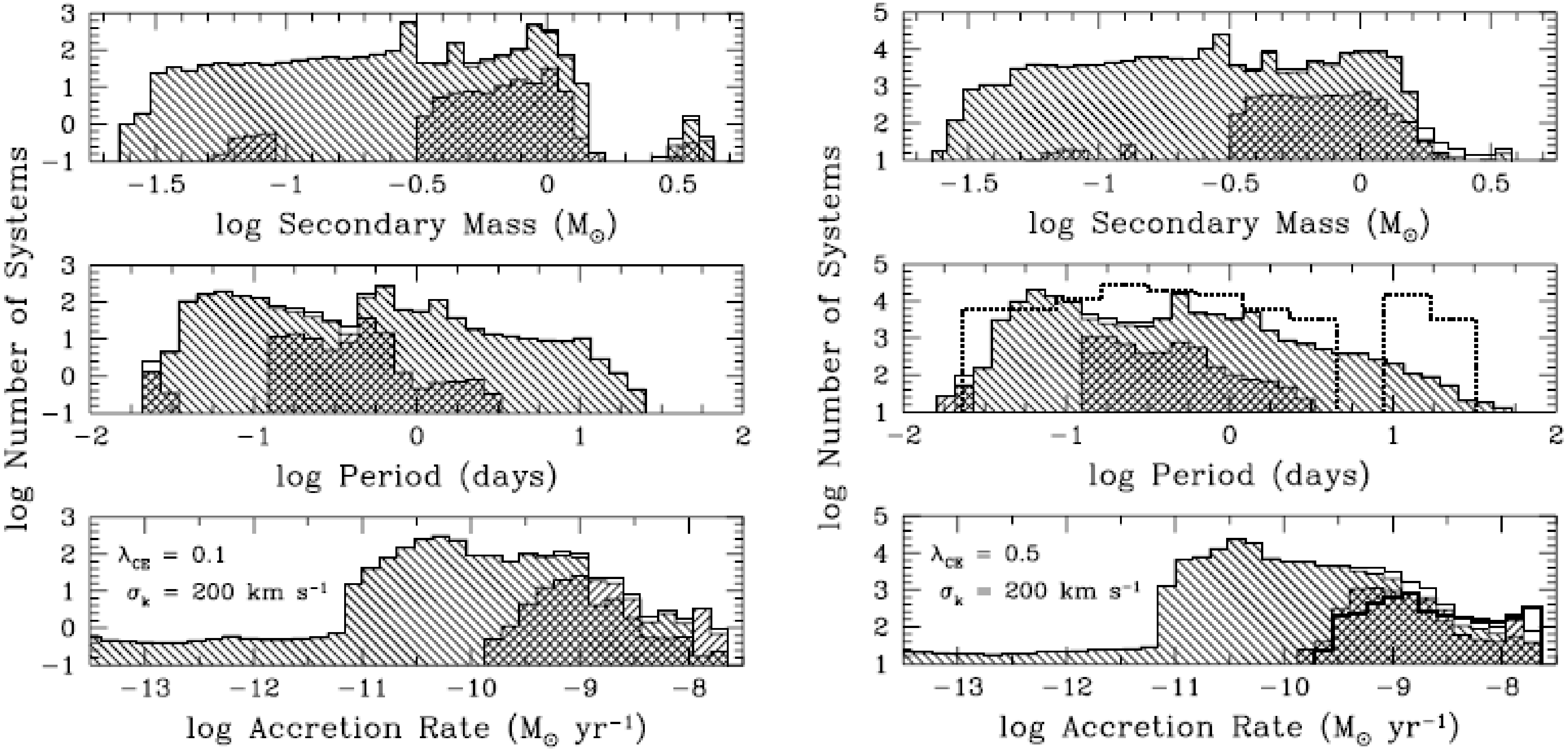
birthrate: $10^{-4} - 10^{-6}\,\mathrm{yr}^{-1}$

- ▷ consistent with pulsar birthrate (e.g. Lorimer 1995)
- ▷ but overproduces I/LMXBs by a factor of 10 – 100

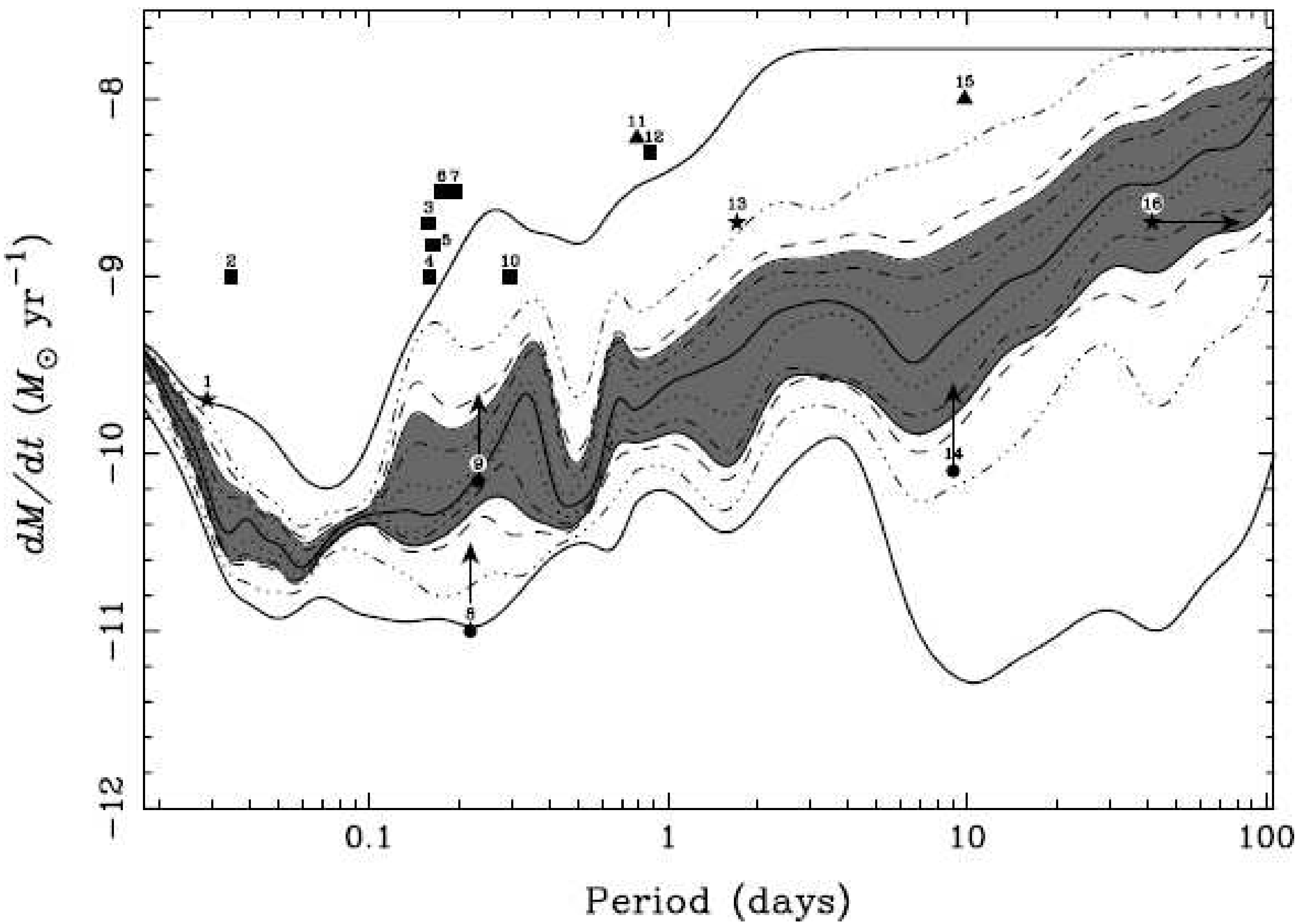
- the luminosity problem: not enough luminous I/LMXBs



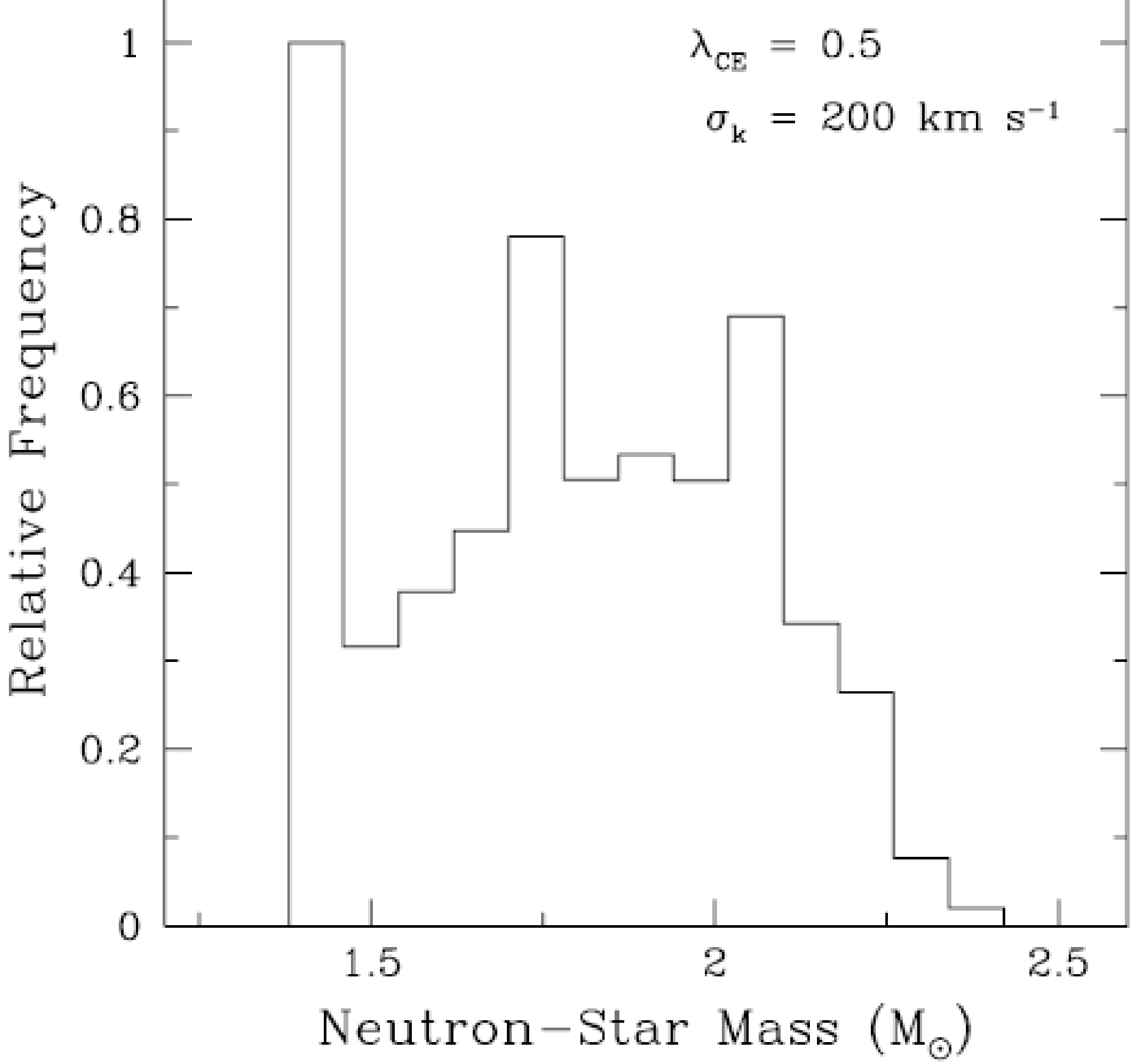
Incipient distribution



Current distribution



−8
−9
−10
−11
−12
0.1
1
10
100
dM/dt (M⊙ yr−1)
Period (days)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16



$\lambda_{CE} = 0.5$
$\sigma_k = 200$ km s^{-1}
Relative Frequency
Neutron–Star Mass ($M_\odot$)
0
0.2
0.4
0.6
0.8
1
1.5
2
2.5

Problems with the standard Model for LMXBs

- the formation of LMXBs requires a very contrived evolution:
  - ▷ extreme initial mass ratio
  - ▷ ejection of a massive common envelope by a low-mass star
  - ▷ survival as a bound system after the supernova (eject $< 1/2$ of the total mass or supernova kick)
- LMXBs are very <u>rare objects</u> (1 in 10^6 stars)
- standard theory cannot explain
  - ▷ orbital period distribution: different from CV distribution
  - ▷ luminosity distribution: too many luminous systems
- the problem of the missing intermediate-mass X-ray binaries (should be the most common)

- LMXB/ms-pulsar statistics (e.g. in globular clusters [Fruchter])

$$\frac{\#\text{ of LMXBs}}{\#\text{ of ms pulsars}} \simeq \frac{\text{lifetime of LMXBs}}{\text{lifetime of ms pulsars}}$$

$$\sim 5 \times 10^9 \text{ yr}$$

$$N_{LMXB} \approx 10$$

$$N_{PSR} \approx 1500 \, \frac{\overbrace{(1+b)}^{\text{binary correction}}}{\underbrace{f}_{\text{beaming factor}}} \simeq 10^4$$

$$\rightarrow \boxed{t_{LMXB} \sim 10^7 \text{ yr}}$$

  - ▷ implied LMXB lifetime too short by a factor of 10 to 100 both in globular clusters and in the Galaxy

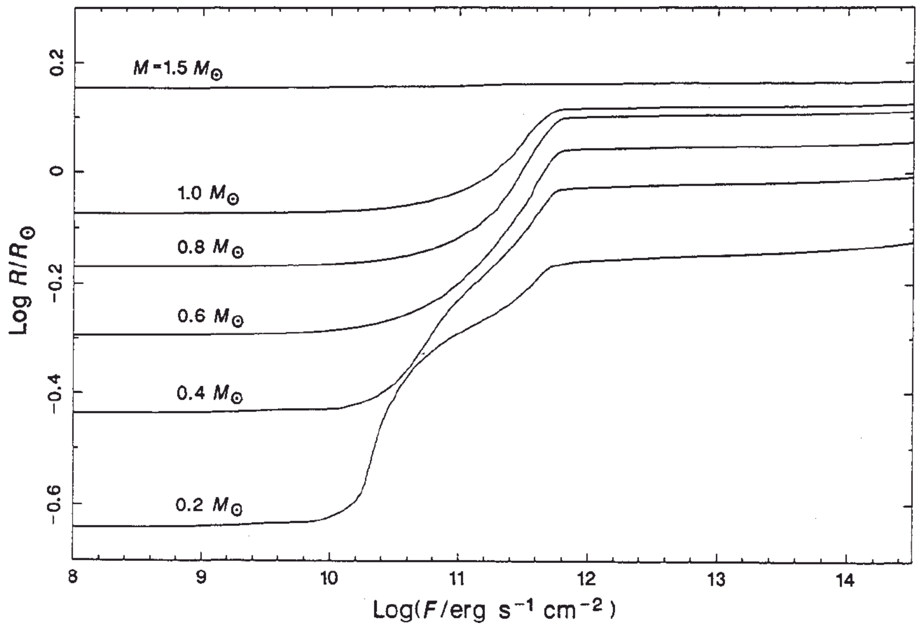
Possible solutions

- different channel for the formation of ms pulsars
  - ▷ accretion-induced collapse
  - ▷ formation from intermediate-mass X-ray binary population in the past
- X-ray irradiation
- irradiation-driven wind (Ruderman et al. 1988)
  - ▷ self-sustained evolution where accretion-powered illumination drives sufficient mass transfer to maintain illumination
  - ▷ $\dot{M}_{\rm rad} \simeq 10^{-7}\,M_\odot\,{\rm yr}^{-1}\,f\,\left(\frac{L_{\rm eff}}{10^{36}}\right)\,{\rm erg\,s}^{-1}$
  - ▷ needs hard X-rays, gamma rays, energetic particles
  - ▷ efficiency ($f \simeq 10^{-3} - 10^{-2}$) may not be efficient enough

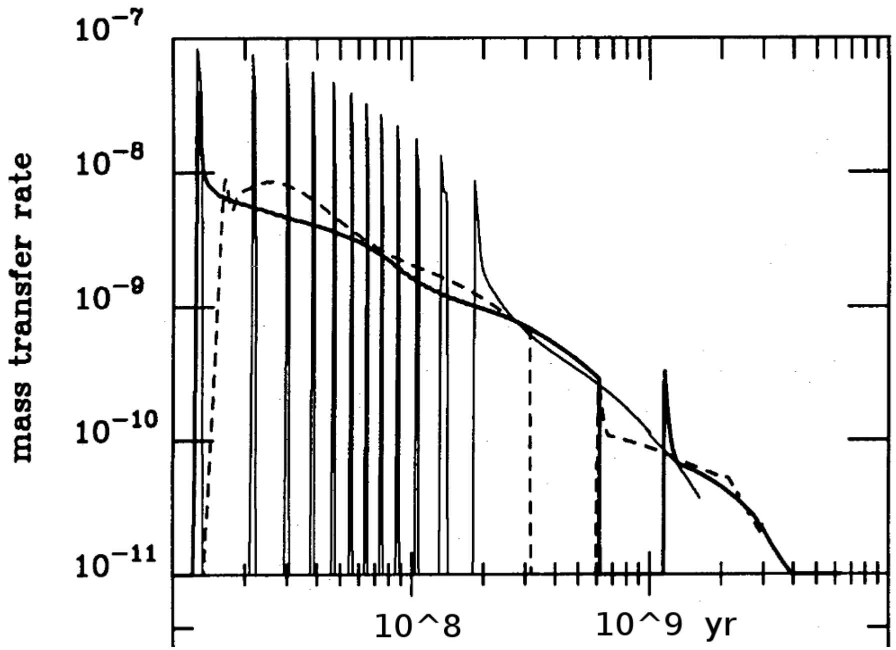
- irradiation-driven expansion (Podsiadlowski 1991)
  - ▷ if companion has a convective envelope
  - ▷ if irradiation $T > 10^4\,K$ (ionization T of H)

→ drives mass transfer

- mass-transfer cycles
  - ▷ $\dot{M}$ 20 times larger for 1/20 the time
  - ▷ shorter X-ray active phase
  - ▷ higher mean luminosity
  - → solves overproduction and luminosity problem
- main problem: one-sided irradiation limits the expansion (compared to spherical illumination)



Podsiadlowski (1991)



Hameury et al. (1993)

Phillips & Podsiadlowski (2002)