Mass Transfer Mechanisms and Mass Transfer Rates in Binaries

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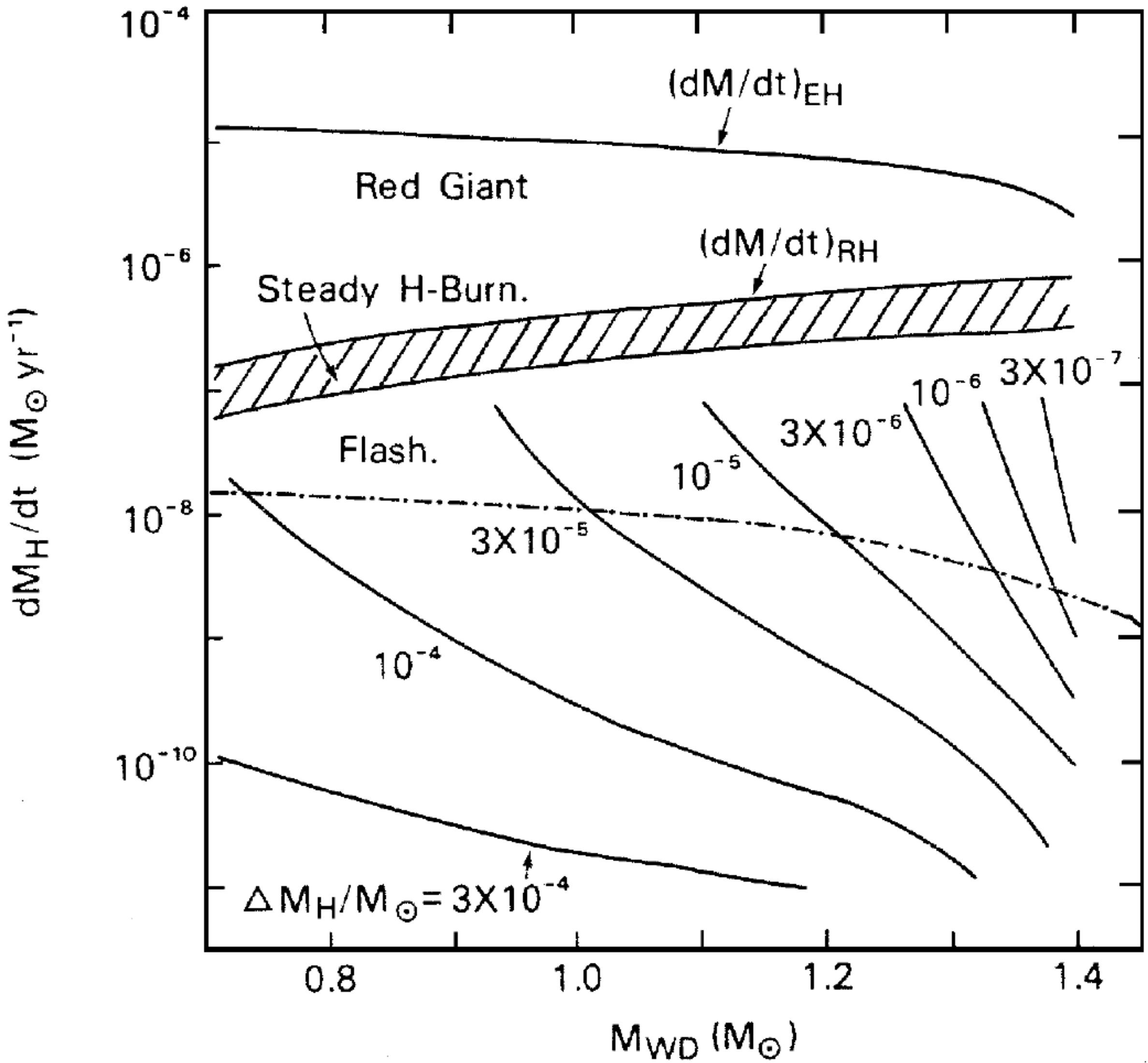


Figure 5 Regimes of steady nuclear burning, weak flashes (cyclic burning), and strong flashes (novae) in the $\dot{M}$–M_{WD} plane (cf Fujimoto 1982a,b, Nomoto 1982, DiStefano & Rappaport 1995). The ΔM_H values indicate envelope masses (for a given accretion rate) at which burning is ignited. Below the *dash-dot line*, flashes produce nova explosions.

> 1Msun White Dwarfs:

For steady burning on the WD surface, the mass-transfer rate should be ~(1-4).10^{-7}Msun /yr. At larger rates burning is also steady, but X-rays don't come out.

For accretion rates > 10^{-8} Msun /yr, the flashes might be weak and burned matter may possibly be retained (?) (But see Bildsten's Wednesday talk!).

Stellar Timescales

Nuclear Timescale: time to exhaust its hydrogen fuel:

$$\tau_n \simeq 10^{10} \frac{M}{M_\odot} \frac{L_\odot}{L} \mathrm{yr} \quad = 10^{10} M^{-2.5} \mathrm{yr} \qquad (2)$$

(M in solar units and ≥ 1)

Thermal timescale: time to emit the star's thermal energy content at its present Luminosity

According to the Virial theorem, $E_{th} = -0.5\, E_{pot,grav} \sim GM^2/R$, so $\tau \sim GM^2/RL$

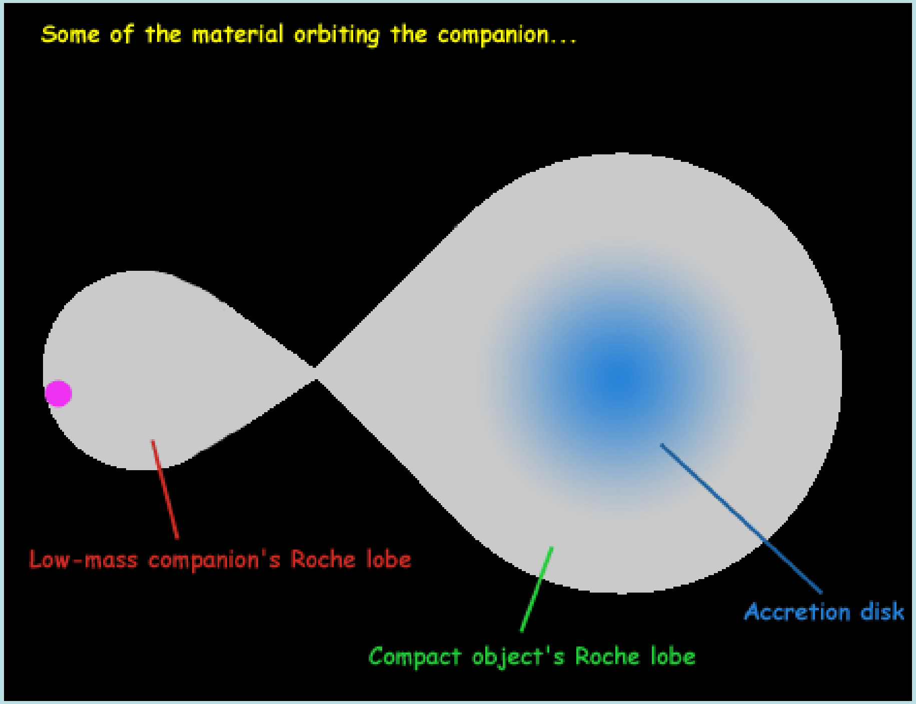
$$\tau_t \simeq 3.1 \times 10^7 \left(\frac{M}{M_\odot}\right)^2 \frac{R_\odot}{R} \frac{L_\odot}{L} \mathrm{yr} \quad = 3.1 \times 10^7 M^{-2} \mathrm{yr} \qquad (3)$$

Dynamical Timescale = Pulsational timescale = time to restore Hydrostatic Equilibrium = R/c_{sound}

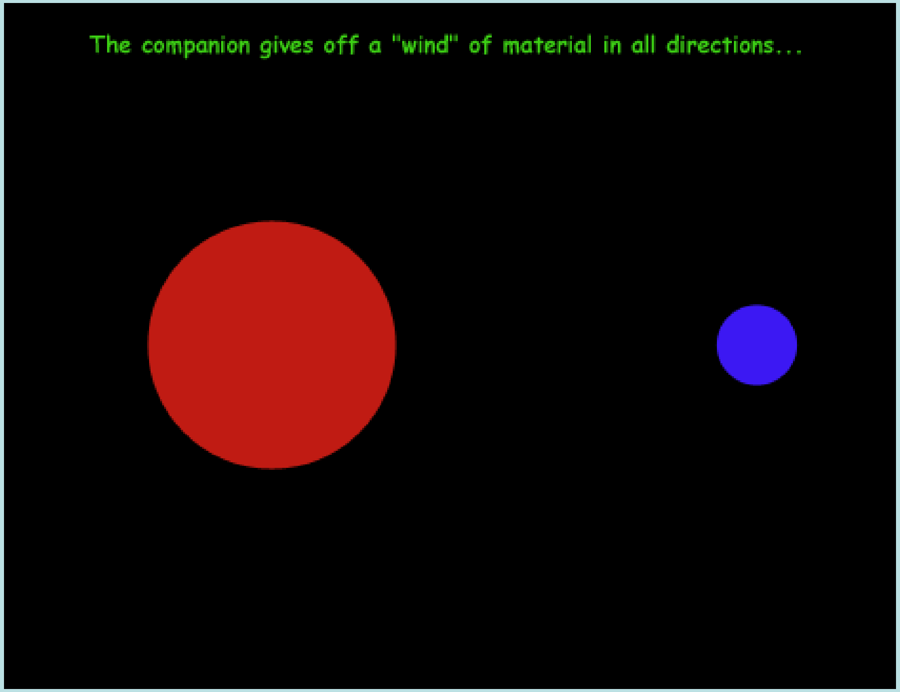
$$\tau_d \simeq 0.04 \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{R}{R_\odot}\right)^{3/2} \mathrm{days} \quad = 50 \min (\rho_{Sun}/\rho)^{0.5} \qquad (4)$$

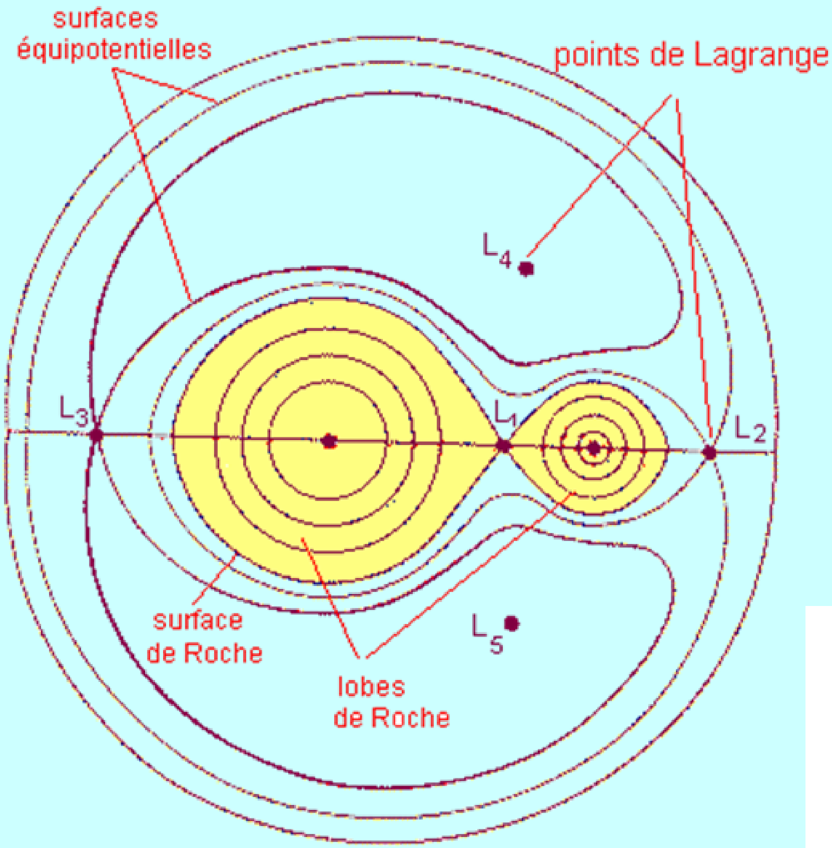
Two possible ways for capturing matter from a companion

Roche-lobe overflow



Stellar wind accretion

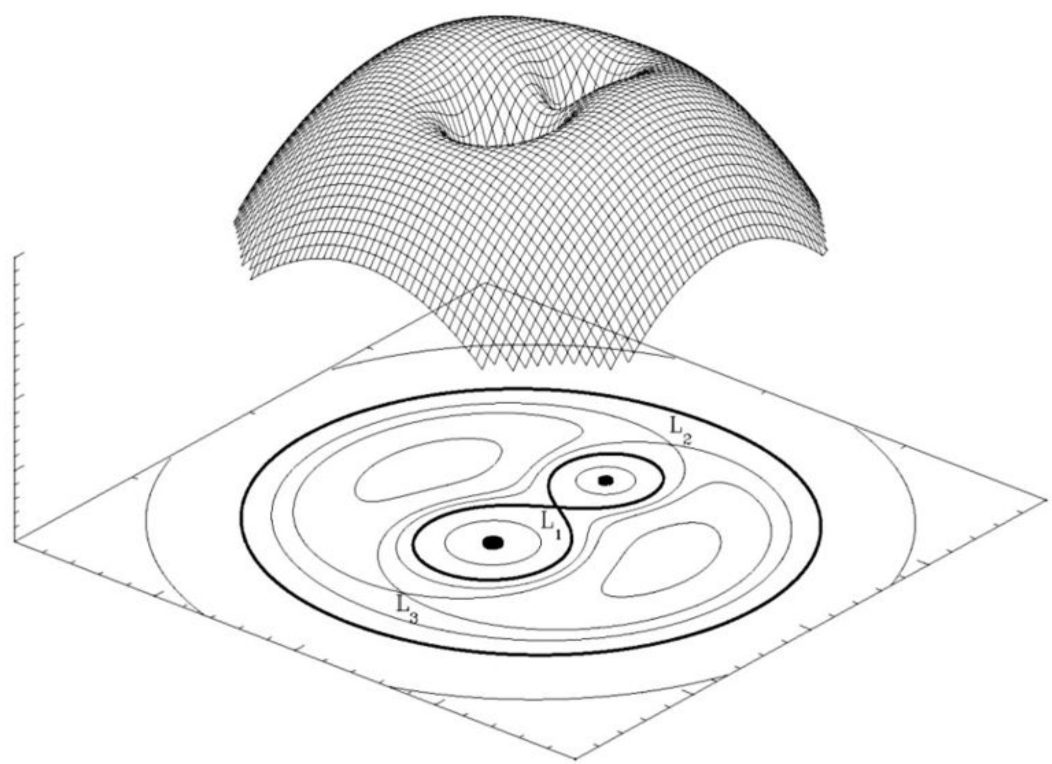


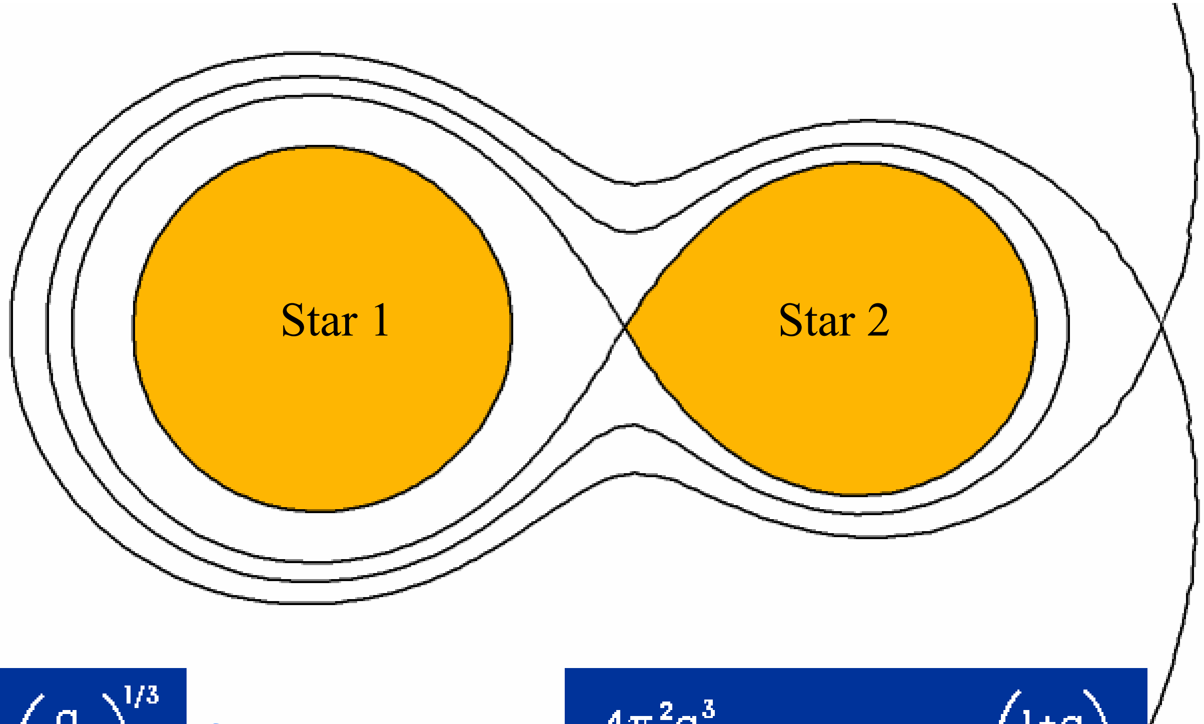


Potentiel de gravitation
dans un système binaire

Lagrangian equipotential surfaces and Roche Lobes are defined in a coordinate system co-rotating with the binary orbital motion; also the stars are assumed to be co-rotating with the system (they stand still in this system).

(The sloping down of the potential beyond L_2 and L_3 is purely an artifact of the rotation of the coordinate system).





$M_2 / M_1 = q$

$$\frac{R_2}{a} = 0.46 \left(\frac{q}{1+q}\right)^{1/3}$$ for $0 < q < 0.8$

$$\frac{4\pi^2 a^3}{GP^2} = M_1 + M_2 = M_2\left(\frac{1+q}{q}\right)$$

$$\rho_2 = \frac{M_2}{\frac{4}{3}\pi R_2^3}$$

$$\rho_2 \simeq 100\, P^{-2}(h)\ \mathrm{g\ cm^{-3}}$$

The mean density of the Roche-lobe filling star is only a function of the orbital period!

$$\frac{R_2}{a} = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln\left(1 + q^{1/3}\right)},$$

(Eggleton's formula ,1983; valid for all values of q)

Simplest Case: **total mass** and **total orbital angular momentum conserved**
(in most cases rotational angular momentum of components much smaller than orbital angular momentum (but not always!)) ; orbits are assumed circular

$$M_1 + M_2 = \text{constant}, \longrightarrow \dot{M}_1 = -\dot{M}_2 \quad (7)$$

$$J_b = M_1 M_2 \sqrt{\frac{Ga}{M_1 + M_2}} = \text{constant}, \quad (8)$$

Combination of (7) and (8) gives:

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}_b}{J_b} - 2\left(1 - \frac{M_2}{M_1}\right)\frac{\dot{M}_2}{M_2}. \quad (9)$$

If J_b = constant, then: since $\dot{M}_2 < 0$: if $M_2 > M_1$, orbit shrinks, in opposite case it widens

$$\frac{a_f}{a_i} = \left(\frac{M_{1i} M_{2i}}{M_{1f} M_{2f}}\right)^2 \quad (10)$$

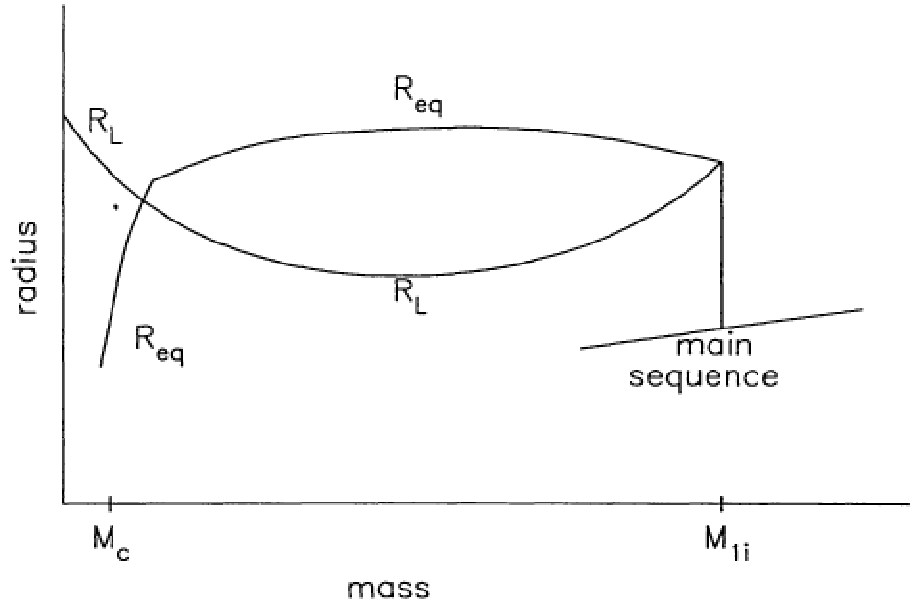
i = initial, f = final

$$\frac{P_{bf}}{P_{bi}} = \left(\frac{M_{1i} M_{2i}}{M_{1f} M_{2f}}\right)^3. \quad (11)$$

Once the more massive star overflows its Roche lobe and transfers matter to its companion, its Roche-lobe radius *shrinks* while its thermal equilibrium radius stays about the same; if it has a radiative envelope the star temporally shrinks due to the mass loss, but it then expands on a thermal timescale to restore its thermal equilibrium. As a result it continues to transfer matter until it has become the less massive component of the system and further mass transfer causes its Roche lobe to expand. The entire process takes ~ τ(thermal):

$$M_{dot} \sim 0.8M/\tau_{(thermal)} \sim 0.8M^3/(3.10^7) \quad [M_{sun}/yr]$$

→ for $M \geq 1.5 M_{sun}$, $M_{dot} \geq 10^{-7}$ M_{sun}/yr



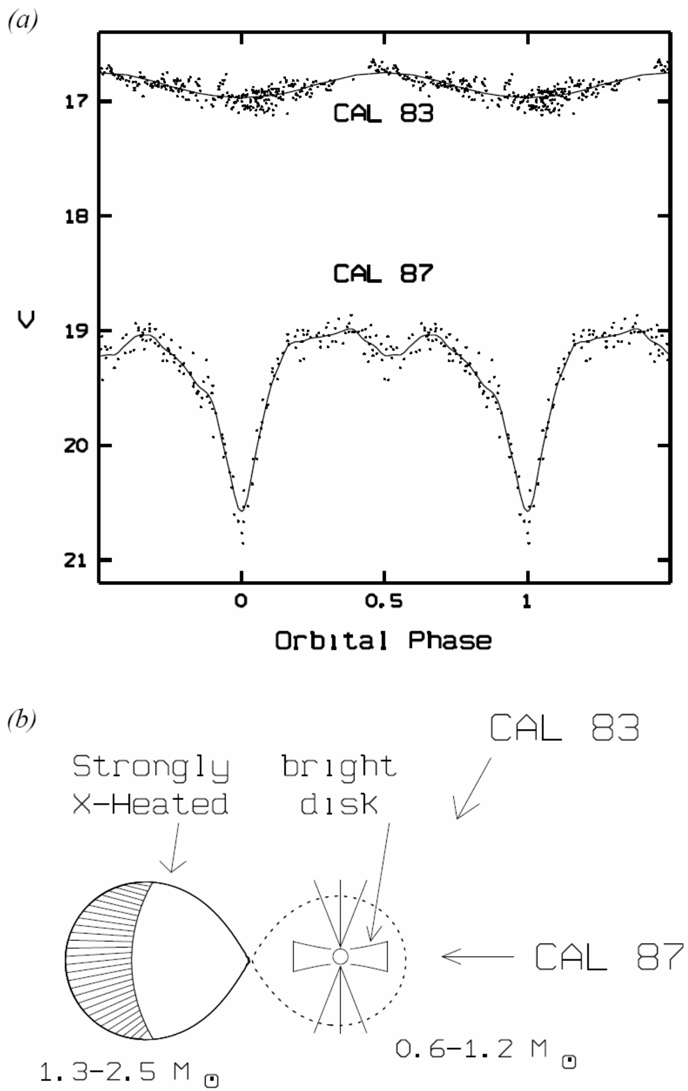


Figure 3 (*a*) Optical light curves in the Johnson V-band of CAL 83 and CAL 87 plotted on the same scale for comparison. The *solid curves* give the mean light curves. The upper light curve is adapted from Smale et al (1988), the lower light curve from Schmidtke et al (1993). (*b*) Schematic model for explaining the optical light curves of CAL 83 and 87: The main light sources in the systems are the very bright accretion disk and the X-ray heated side of the donor star. In CAL 87 the accretion disk is regularly eclipsed; CAL 83 is seen at low inclination, such that only the heating effect is observed [after van den Heuvel et al (1992); for a refined model, see S Schandl et al (1996); see also section on The "Standard" CBSS].

P_{orb} = 1.04 days

P_{orb} = 10.6 hours

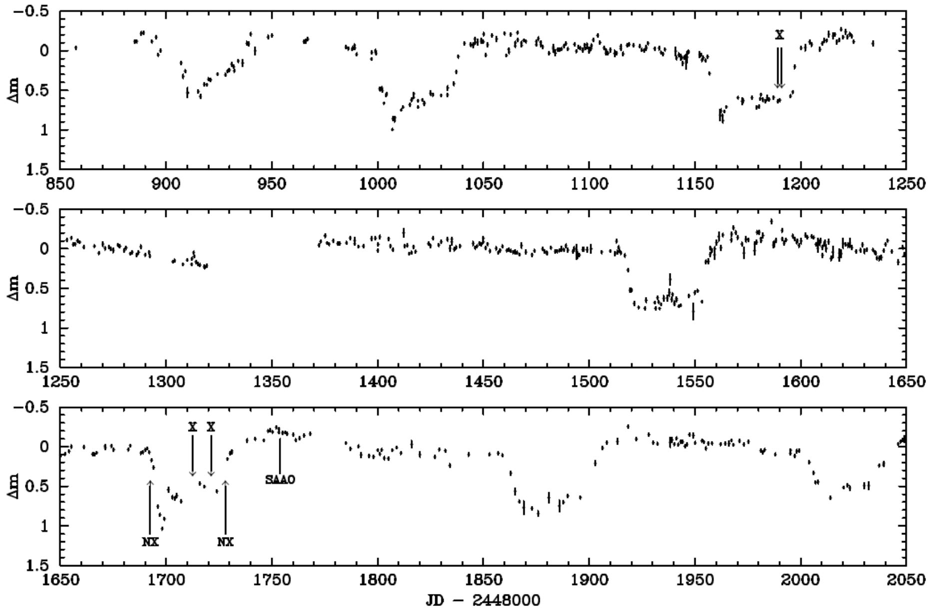


Figure 7 Optical light curve of RX J0513.9-6951 from August 22, 1992, to November 27, 1995, obtained with the MACHO project. Downward and upward *vertical arrows* indicate times at which the system was known to be on (X) or off (NX) in X rays, respectively (from Southwell et al 1996b).

P_{orb} = 18,3 hours

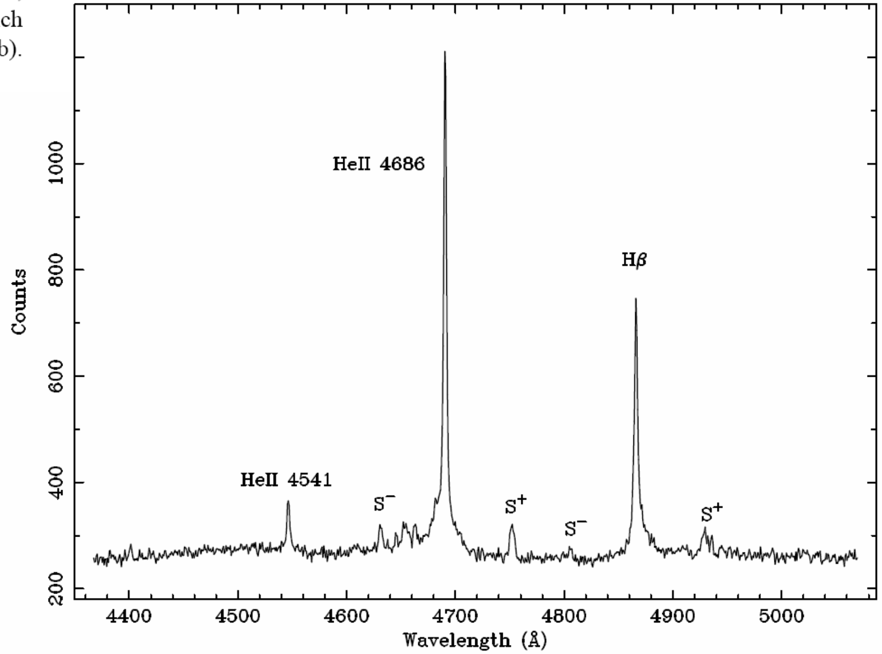


Figure 8 Average blue spectrum of RX J0513.9-6951. The principal He II and H emission features are marked, along with their associated Doppler-shifted components (from Southwell et al 1996b).

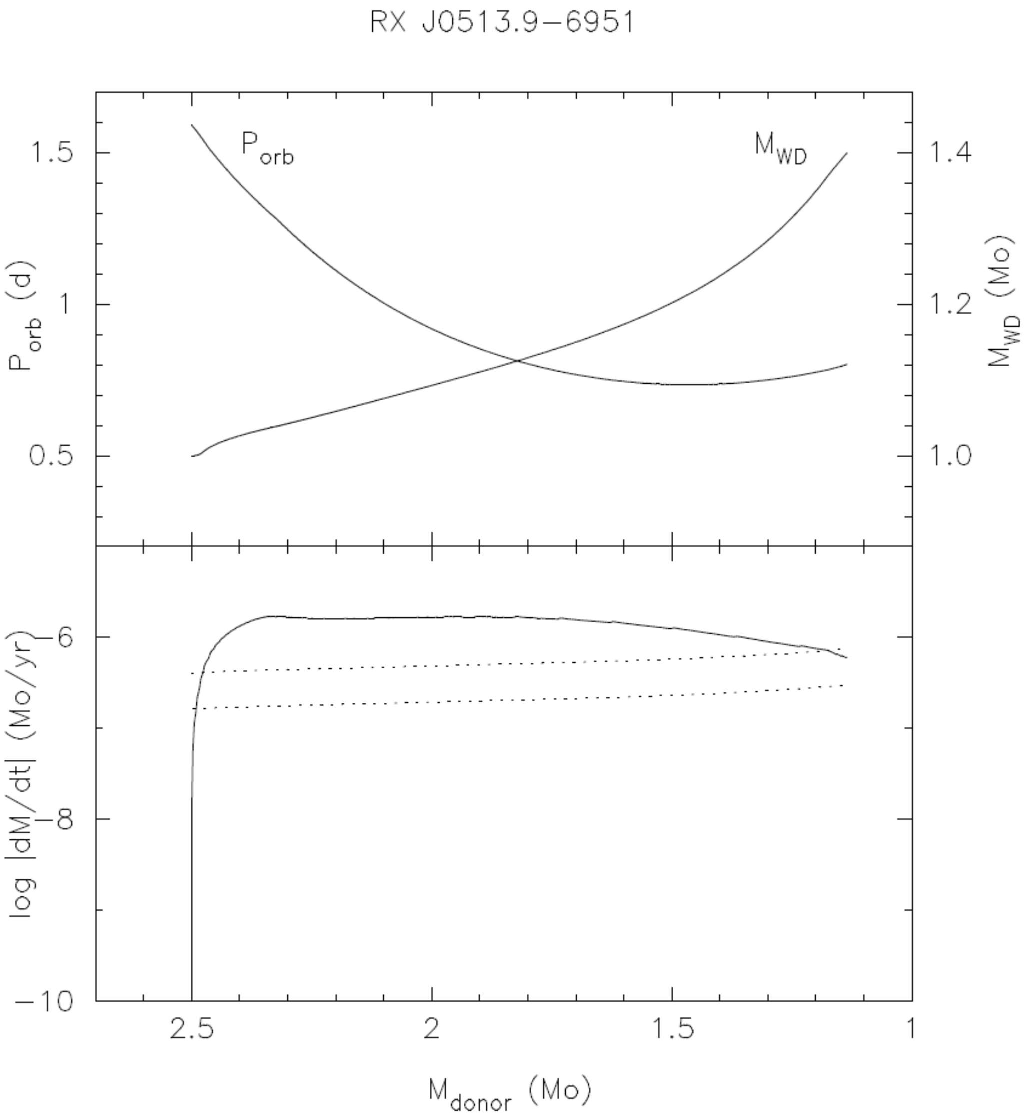
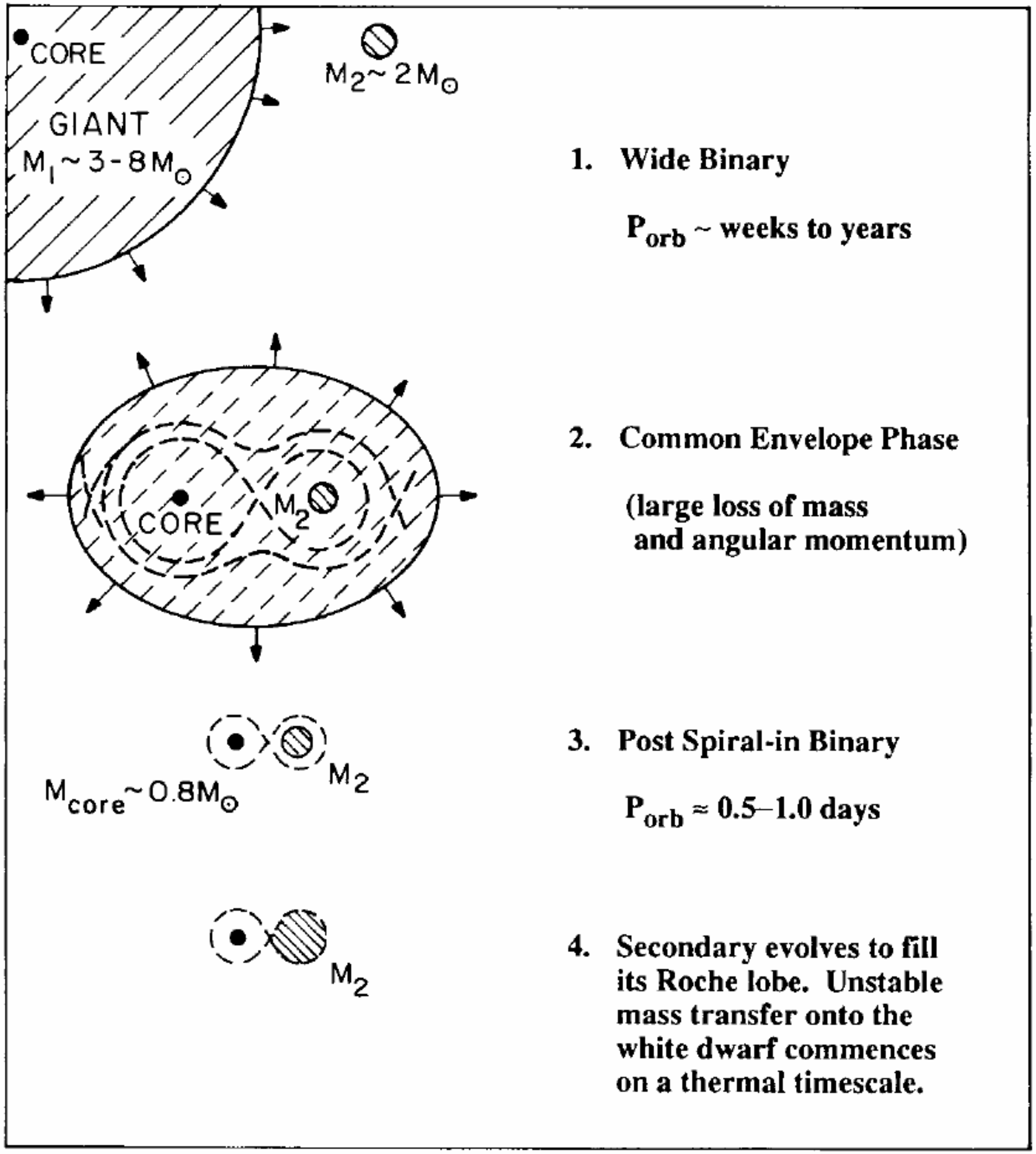


Figure 11 Evolution of orbital period, white dwarf (WD) mass, and $\dot{M}$ of a CBSS with an initial donor mass of 2.5 $M_\odot$ and an initial WD mass of 1 $M_\odot$, in which the mass-transfer rate is mostly $\sim 10^{-6}$ $M_\odot \mathrm{year}^{-1}$ (from X Li, in preparation). *Dashed lines*: boundaries of the stable burning region without radius expansion. Transferred mass in excess of the max. rate for stable burning is assumed to be ejected with specific orbital angular momentum of the WD



Exactly the same evolutionary scenario as for making CV-binaries.
The only difference is that here M2 is larger: anywhere between ~1.5 and ~5 Msun

Figure 9 Evolutionary scenario for the formation of a close binary supersoft X-ray source (cf text; from Rappaport & DiStefano 1996).

Non-conservative Evolution: losses of mass and orbital angular momentum from the system.

A lost mass element is a "third body" in the system. As there is no general analytic solution of the 3-body problem, there is no general solution for this case.

Approach: prescribe a "mode of mass and orbital angular momentum loss" and calculate how this "mode" causes the orbit to change.

For a general "cookbook" of non-conservative "modes" and their results: see Soberman, Phinney and vdH, 1997, A&A, 327, 620-635.

Simplest case: No mass loss from the system,

Only loss of orbital angular momentum, due to:

-Gravitational radiation losses

and/or

-“Magnetic Braking”

The latter means: rotational braking of a solar-type star (with convective envelope) due to a magnetically coupled stellar wind (Verbunt and Zwaan 1981)

Solar corona magnetically co-rotates with Sun out to ~ $10R_{sun}$ causing the solar wind to carry off rotational angular momentum (but negligible mass).

Young G-stars in the Pleiades (~ 70 million years) rotate ~ 22 km/s and in Hyades (700 million yrs) rotate ~ 8 km/s. Sun (4.6 billion yrs) rotates 2 km/s. From this one can empirically estimate the slowdown torque T_{mb} as a function of ω(rot) for solar type stars (Skumanich,1972).

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}_b}{J_b} - 2\left(1 - \frac{M_2}{M_1}\right)\frac{\dot{M}_2}{M_2}. \qquad (9)$$

$R_L/a = 0.4622\,(M_2/(M_1 + M_2))^{1/3}$ ⟶ $dR_L/R_L = da/a + 1/3\,(dM_2/M_2)$

Substitution of the latter into eq. (9) yields:

$R_{Ldot}/R_L = 2\,J_{bdot}/J_b - 2\,(5/6 - M_2/M_1)(M_{2dot}/M_2)$

For a detailed treatment of mass transfer in X-ray Binaries: see Verbunt, Annual Rev. A&A, 1993, which we largely follow here

Relation between Orbital Period and Donor Mass

(From Verbunt,1993, Annual Rev.)

By combining Kepler's law with Equation 6, we get an approximate relation between orbital period and the mass and radius of the Roche-lobe-filling star:

$$P_{\rm orb} \simeq 8.9\,{\rm hr}\left(\frac{R_2}{R_\odot}\right)^{3/2}\left(\frac{M_\odot}{M_2}\right)^{1/2}. \qquad (25)$$

(:) $\rho_2^{-1/2}$

Table 2 Mass-radius relations and derived mass-orbital-period relations for low-mass X-ray binaries[a] and CV binaries

Main sequence	$R_2/R_\odot = M_2/M_\odot$	$P_b = 8.9\ {\rm hr}\ M_2/M_\odot$
He main sequence	$R_2/R_\odot = 0.2 M_2/M_\odot$	$P_b = 0.89\ {\rm hr}\ M_2/M_\odot$
White dwarf	$R_2/R_\odot = 0.0115(M_2/M_\odot)^{-1/3}$	$P_b = 40\ {\rm s}\ M_\odot/M_2$

[a] Valid for donors in thermal equilibrium.

The change in radius of the donor star may be due to internal evolution of the star, or to the mass-transfer process. We may thus write

$$\frac{\dot{R}_L}{R_L} = \left(\frac{\dot{R}_2}{R_2}\right)_{\rm ev} + \frac{d\ln R_2}{d\ln M_2}\frac{\dot{M}_2}{M_2} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_2}{M_2}\left(\frac{5}{6} - \frac{M_2}{M_1}\right). \qquad (26)$$

Assume: $R_2 = K\,M_2^{n}$

This equation shows that mass transfer may be driven by loss of angular momentum from the binary ($\dot{J} < 0$), or by expansion of the donor star ($\dot{R}_2 > 0$) due to, for example, the ascent of the donor on the (sub)giant branch, or due to irradiation of the donor. We discuss these possibilities in turn.

It was realized by Kraft et al (1962) that gravitational radiation provides a sufficiently high loss of angular momentum to drive observable mass transfer in a close binary. The loss of angular momentum via gravitational radiation may be written (Landau & Lifshitz 1962):

$$-\left(\frac{\dot{J}}{J}\right)_{\mathrm{GR}} = \frac{32G^3}{5c^5}\frac{M_1M_2(M_1+M_2)}{a^4}. \tag{27}$$

If we write the mass-radius relation of the donor star as $R_2 \propto M_2^n$, Equation 26 can be rewritten as

$$-\frac{\dot{J}}{J} = -\frac{\dot{M}_2}{M_2}\left(\frac{5}{6}+\frac{n}{2}-\frac{M_2}{M_1}\right). \tag{28}$$

This equation assumes that no mass is lost from the binary; extension to the more general case is straightforward (see Equation 14).

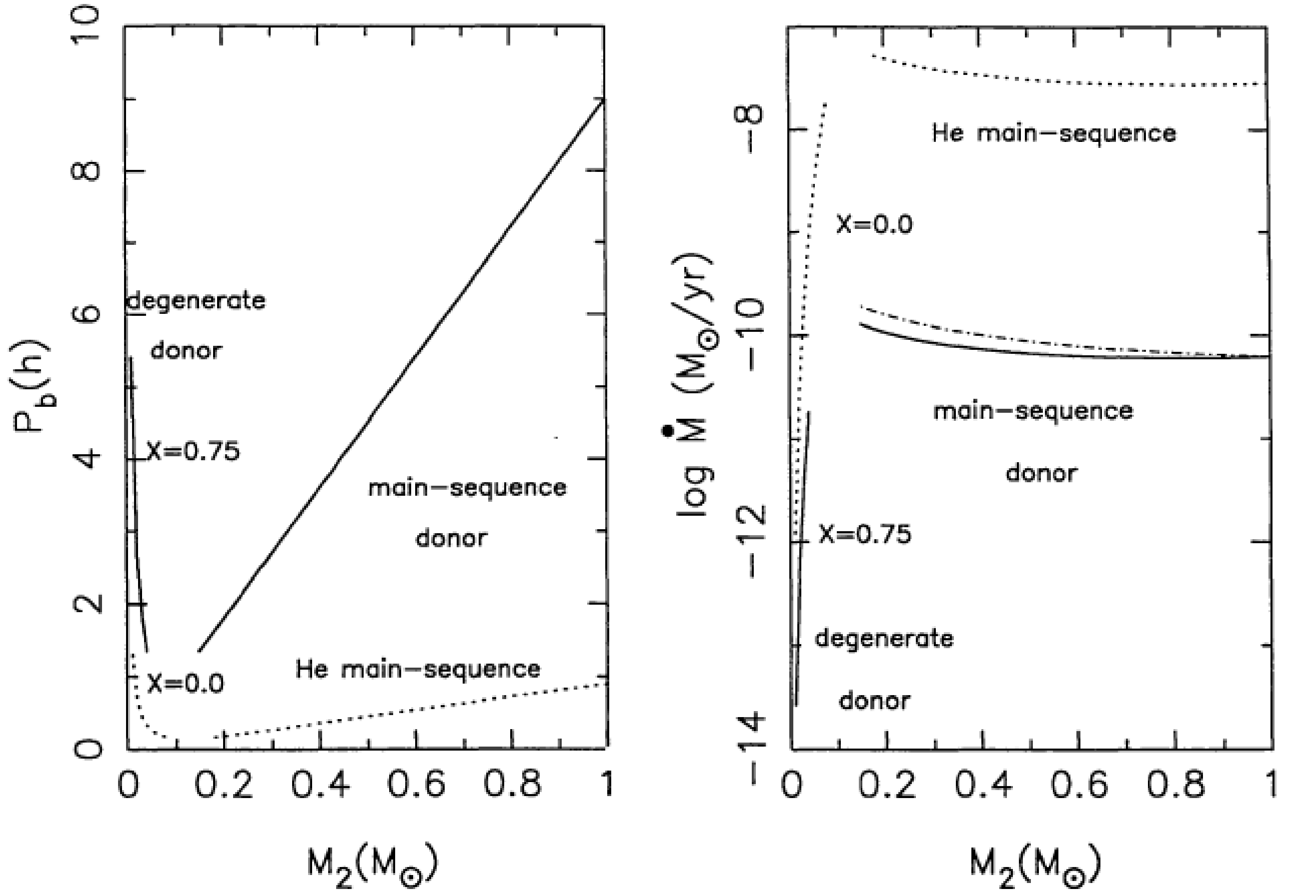
To estimate the importance of braking in the evolution of low-mass X-ray binaries, Verbunt & Zwaan (1981) parametrized the angular momentum loss $\dot{J}_{\mathrm{mb}}$ from single G-stars, assuming that the magnetic field strength and the stellar wind depend on mass, radius, and rotation velocity only. By applying this to a main-sequence donor in a binary, they find:

$$\frac{\dot{J}_{\mathrm{mb}}}{J_{\mathrm{b}}} = \frac{-3.8\times10^{-30}R_{\odot}^{4-\gamma}(M_1+M_2)R_2^{\gamma}\omega^2}{M_1a^2} \tag{29}$$

Purely Gravit. Radiation-driven mass transfer

(Verbunt 1993)

Holds for LMXBs and CV binaries alike



Observed mass transfer rates in CVs are ~ 10 to 100 times higher than GR alone can give (the same holds for the LMXBs)

Patterson (1983) gives an approximate mean relation for this correlation:

$$\dot{\mathscr{M}} = 6 \times 10^{-12} \, (P_{\rm orb}/1 \text{ hr})^{3.3 \pm 0.3} \, M_{\odot} \text{ yr}^{-1}, \quad (41)$$

which holds for orbital periods outside the 2–3 hr period gap. The spread of observed values for $\dot{\mathscr{M}}$ about this relation is about a factor of 5.

With this formula, a system with P_{orb} ~ 8 hours has M_{dot} ~ 6.10^{-9} M_{sun}/yr

Magnetic Braking

RAPPAPORT, VERBUNT, AND JOSS *Ap.J. 275,713, 1983*

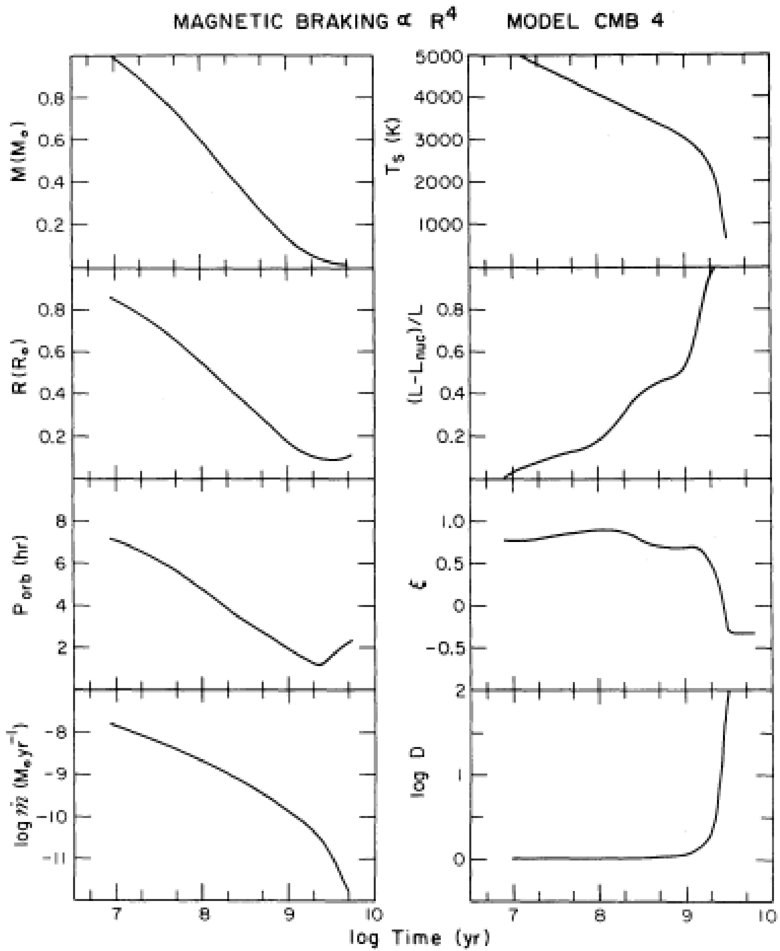


FIG. 2

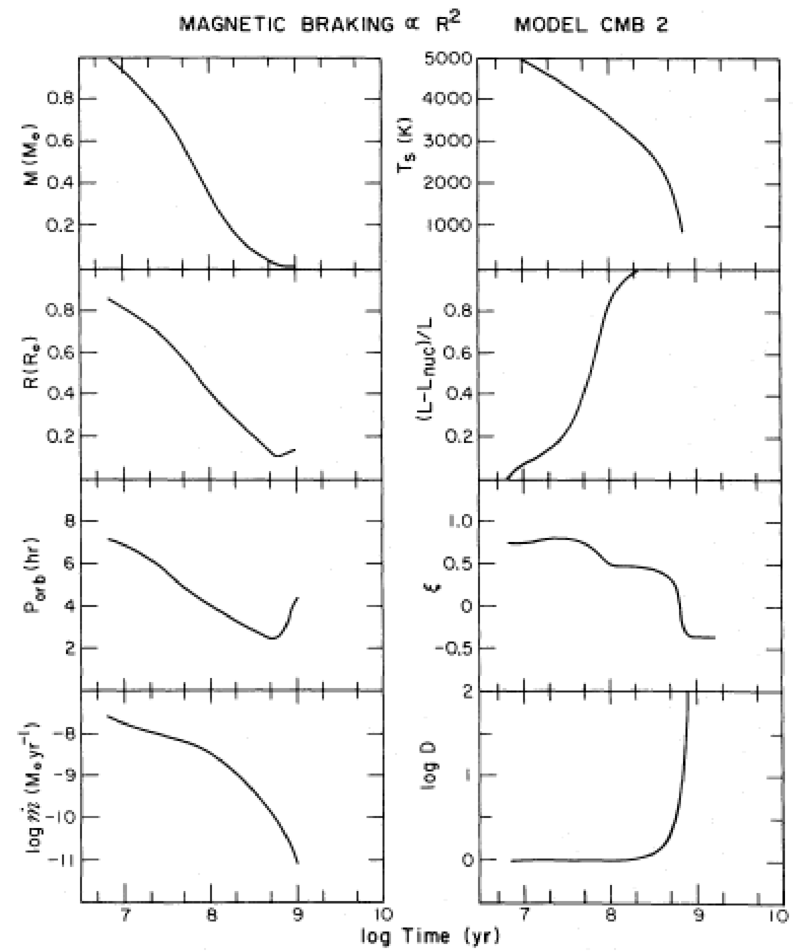


FIG. 3

FIG. 2.—Calculated evolution with continuous magnetic braking given by equation (36) with $\gamma = 4$: model CMB 4. The initial parameters of this system are $\mathscr{M} = 1.2\ M_\odot$, $M = 1.0\ M_\odot$, $P_{orb} = 7^h1$, and $(X, Y, Z) = (0.70, 0.28, 0.02)$. Alexander (1975, 1980) opacities without grains (see RJW) were assumed, and gravitational radiation losses were included in all models. Several of the binary system parameters (the mass, M, and radius, R, of the secondary, the orbital period, P_{orb}, and the mass accretion rate onto the primary, $\dot{\mathscr{M}}$) are shown in the left-hand panel as functions of elapsed time from the start of the evolution. The evolution of some additional parameters of the secondary [its effective temperature, T_s, fractional luminosity deficit, $(L - L_{nuc})/L$, stellar index, $\xi = (M/R)(dR/dM)$, and ratio, D, of total to ideal gas pressure in the convective envelope] are shown in the right-hand panel (see text and RJW for explanations of the significance of these parameters).

FIG. 3.—Calculated evolution with continuous magnetic braking given by equation (36) with $\gamma = 2$: model CMB 2. Compared to model CMB 4 (with $\gamma = 4$), this assumed braking law provides a relatively high magnetic braking rate when the radius of the secondary is small. The input physics and initial parameter values are otherwise the same as in model CMB 4, and the notation is the same as in Fig. 2.

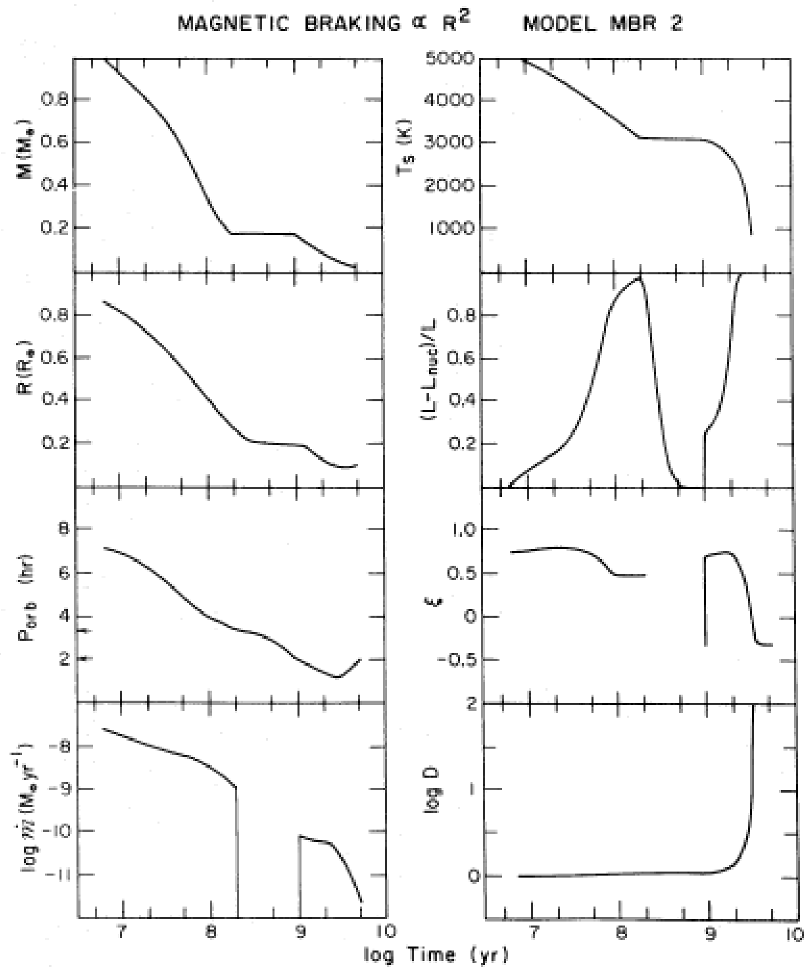


FIG. 4

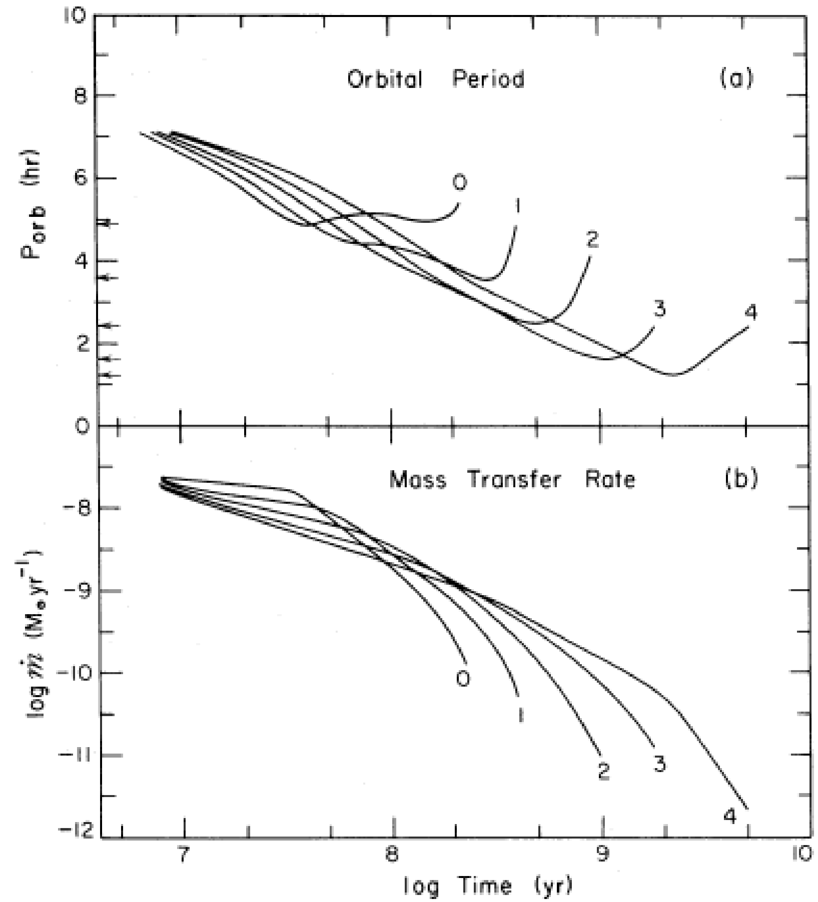


FIG. 5

FIG. 4.—Calculated evolution with magnetic braking, given by eq. (36) with $\gamma = 2$, only while the secondary retains its radiative core: model MBR 2. When the radiative core of the secondary vanishes, at an elapsed time of $\sim 2 \times 10^8$ yr, the magnetic braking is stopped (see § II*b*). The input physics and initial parameter values are otherwise the same as in model CMB 2, and the notation is the same as in Fig. 2.

FIG. 5.—Calculated evolution for a series of continuous magnetic braking models (CMB 0–4). The magnetic braking law is given by equation (36), with the assumed braking index, γ, indicated on each curve. The input physics and initial parameter values of all five models (except for the value of γ) are as described in the caption to Fig. 2. (*a*) Evolution of the orbital period, P_{orb}. Arrows on the ordinate of P_{orb} denote the minimum orbital period attained by the binary for each of the five braking laws. (*b*) Evolution of the mass transfer rate, $\mathscr{M}$.

Rappaport, Verbunt and Joss, 1983(Ap.J.275,713) conclude:

Our results are unambiguous in at least one regard: mass transfer rates in excess of $10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ can be driven by magnetic braking for intervals of time $\gtrsim 6\times10^{6}$ yr when the mass of the secondary is $\sim 1\ M_{\odot}$. The mass transfer rates subsequently decline; however, the rate of decline depends sensitively on the uncertain parameters in the magnetic braking law (see § II*b*).

Implication: if this matter can be retained (weak flashes) the WD in a CV-binary can in this early mass transfer phase grow by some 0.1 M_{sun}

Mass transfer driven by internal evolution of a companion (subgiant or giant)

Webbink, Rappaport and Savonije, 1983, Ap.J. 270,678; Taam, 1983, Ap.J.270,694.

Evolution via Donor Expansion Low-mass red giant with degenerate He core of mass Mc

Results of detailed calculations can be represented with simple polynomial relations in $y \equiv \ln M_c/(0.25M_\odot)$ (Webbink et al 1983):

$$\ln(R_2/R_\odot) = a_0 + a_1 y + a_2 y^2 + a_3 y^3 \tag{30}$$

$$\ln(L_2/L_\odot) = b_0 + b_1 y + b_2 y^2 + b_3 y^3. \tag{31}$$

Luminosity and radius of star depend only on Mc

The values of the fitting constants a_i, b_i depend on the metallicity of the star, and are given for two metallicities, for stars in the Galactic disk, and for stars in low-metallicity globular clusters, in Table 3.

The luminosity on the giant branch is almost completely due to hydrogen shell burning, and is related to the core mass by

$$\dot{M}_c \simeq 1.37 \times 10^{-11} \left(\frac{L}{L_\odot}\right) M_\odot \,\mathrm{yr}^{-1}. \tag{32}$$

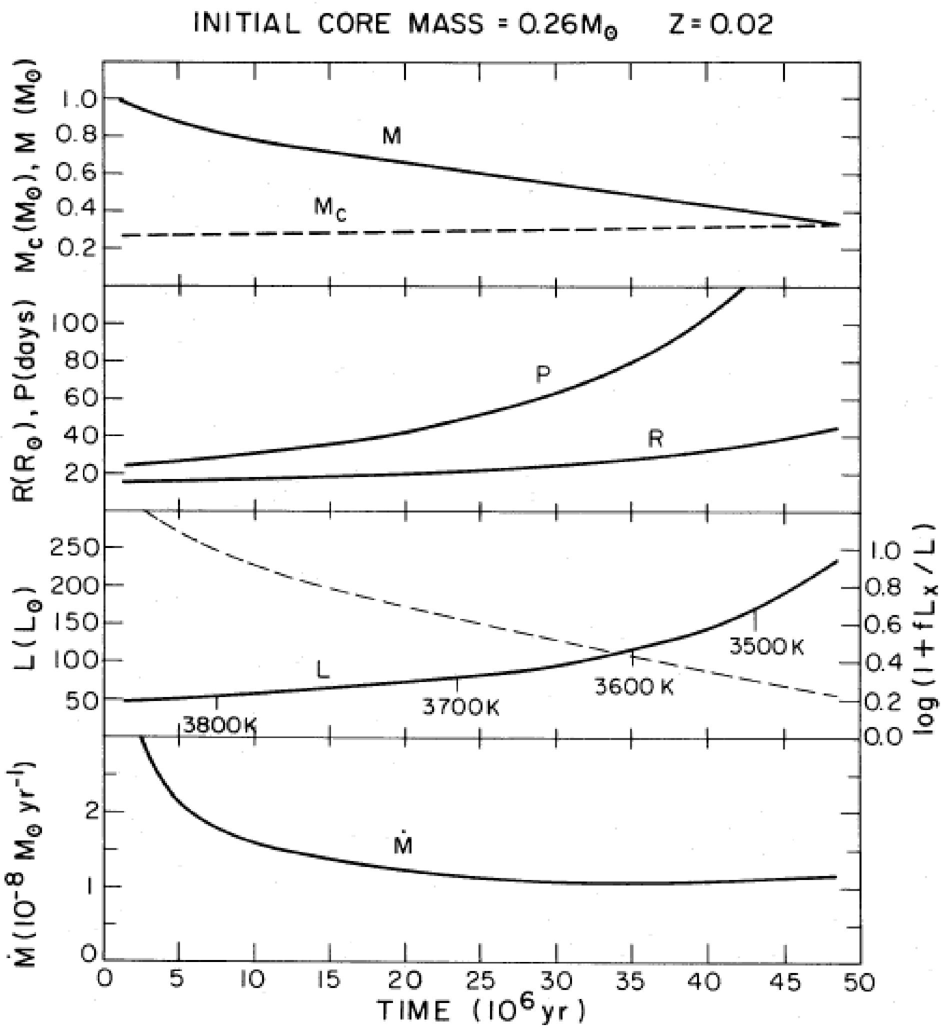
Combining Equations 30 and 32 gives the relation between the change in radius and the change in core mass:

$$\frac{\dot{R}_2}{R_2} = (a_1 + 2a_2 y + 3a_3 y^3)\frac{\dot{M}_c}{M_c}. \tag{33}$$

In the absence of loss of angular momentum, Equation 26 may be rewritten

$$\frac{\dot{R}_2}{R_2} = -2\frac{\dot{M}_2}{M_2}\left(\frac{5}{6} - \frac{M_2}{M_1}\right) \tag{34}$$

which completes the set of equations required to calculate the binary evolution. The orbital period and the two masses determine the radius of the giant via Equation 25 and hence its core mass via Equation 30; the core mass determines the rate of radius expansion via Equation 33, and with this the mass-transfer rate via Equation 34. Thus the evolution can be calculated without resort to complete stellar evolution codes.



For some 50 million years, $M_{dot} > 10^{-8} M_{sun}$ /yr

One can easily accrete > $0.5 M_{sun}$
(if flashes weak)

FIG. 3.—Evolution of a binary system with a secondary component of initial mass 1.0 $M_\odot$, initial core mass 0.26 $M_\odot$, and composition $Y = 0.28$, $Z = 0.02$. From the top, successive panels indicate, as functions of time, (1) total mass (*solid line*) and core mass (*dashed line*) of the secondary; (2) radius of the secondary and orbital period of the binary; (3) intrinsic luminosity (*solid line*) and logarithm of the ratio of intrinsic plus intercepted to intrinsic luminosity (*dashed line*) of the secondary; and (4) mass accretion rate onto the compact star. Conservation of total mass and orbital angular momentum is assumed. An accreting neutron star of radius 10^6 cm and initial mass 1.4 $M_\odot$ is also assumed.

For wide initial orbits (P ~ 50 d to 150 d) mass transfer rates in the range 10^{-7} to 10^{-6} Msun /yr can be achieved, and > 0.50 Msun can be transferred to the WD

Verbunt 1993, Ann.Rev.

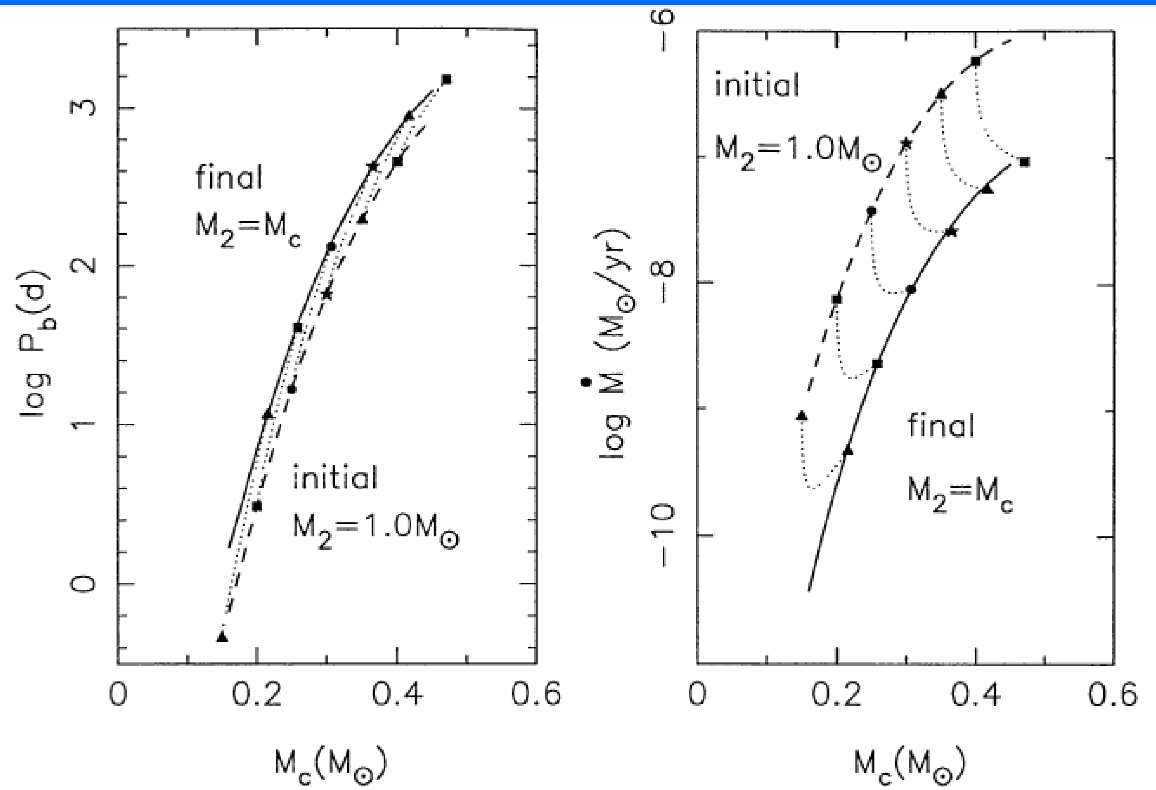


Figure 8 Orbital period and mass-transfer rate as a function of the mass of the donor core M_c, for binary evolution driven by expansion of a giant donor star. The mass-transfer rates shown all assume $M_1 = 1.4M_\odot$ and $\dot{M}_1 = -\dot{M}_2$.

we find that, to an excellent approximation ($\pm 20\%$), the mean mass transfer rate for our models is linearly proportional to the initial orbital period:

$$\langle \dot{M} \rangle \approx -5.3 \times 10^{-10} M_\odot \,\mathrm{yr}^{-1} (P_0/\mathrm{day}). \quad (19)$$

Similarly, owing to the nearly constant amount of mass transferred during tidal interaction ($\Delta M \approx 0.6 \, M_\odot$), the source lifetimes are well approximated ($\pm 12\%$) by

$$\tau_x = t_f - t_0 \approx 1.13 \times 10^9 \,\mathrm{yr} (P_0/\mathrm{day})^{-1}. \quad (20)$$

Webbink, Rappaport and Savonije, 1983 Ap.J.

A final type of binaries with stable thermal timescale mass transfer with large mass and ang. mom. loss from the system: the “intermediate-mass X-ray binary” model:
initial donor mass 1.5 – 5 M_{sun} and not too wide orbits (~ 1 day to ~ 10 days).
(*Tauris et al, 2000, Ap.J.)*

Mass Exchange in a Binary: Nonconservative Case

With both loss of mass AND orbital angular momentum (Verbunt 1993, Annual Rev.)

$$\dot{M}_1 = -\beta \dot{M}_2 \quad \text{or} \quad \dot{M}_1 + \dot{M}_2 = (1-\beta)\dot{M}_2,$$

i.e. a fraction β of the mass lost by the donor star is accreted onto its companion—the rest leaves the system. The mass lost from the system will carry angular momentum. If we write the specific angular momentum of the mass that is lost as α times the specific angular momentum of the mass-losing star, we may replace Equation 8 with

$$\frac{\dot{J}_{\dot{M}}}{J} = \alpha(1-\beta)\frac{M_1}{M_1+M_2}\frac{\dot{M}_2}{M_2}, \qquad (13)$$

The "mass-loss" part of the orbital angular momentum loss

where $\dot{J}_{\dot{M}}$ indicates the loss of angular momentum due to loss of matter.

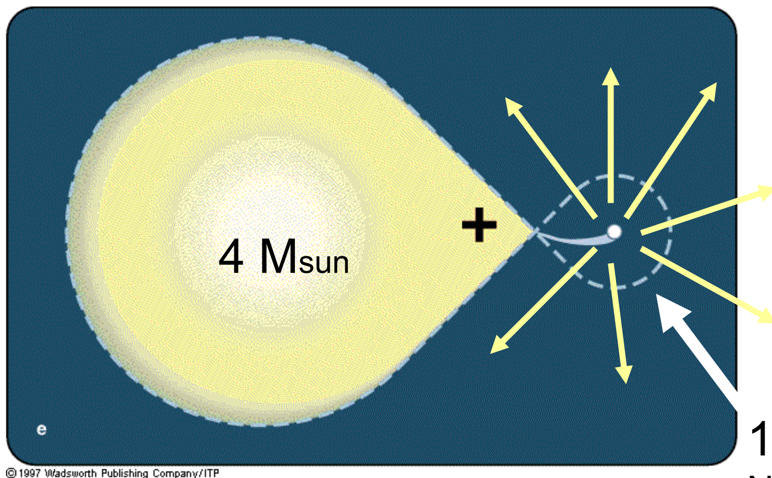
$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_2}{M_2}\left[1 - \frac{\beta M_2}{M_1} - \frac{(1-\beta)M_2}{2(M_1+M_2)} - \alpha(1-\beta)\frac{M_1}{M_1+M_2}\right]. \qquad (14)$$

Jdot is the orbital angular momentum loss due to other causes: Gravitational Radiation,"Magnetic Braking"

To see the effect of mass loss on the orbit, consider the case where almost all the mass lost by the donor is also lost from the system ($\beta \simeq 0$), and where no loss of angular momentum occurs other than that concomitant with the mass loss. In that case, the orbit will widen provided that $\alpha < 1 + M_2/(2M_1)$. This is the case if the mass lost leaves with specific angular momentum equal to that of the mass-losing star, i.e. if $\alpha = 1$. Equation 14 then simplifies into

$$a(M_1+M_2) = \text{constant}. \qquad (15)$$

Taurus, vdH and Savonije, 2000,Ap.J.530



At onset of mass transfer (P_{orb} =4d), the $4M_{sun}$ star has a radiative envelope, resulting in stable transfer on a thermal timescale.

The transferred mass in excess of $\dot{M}_{Edd}$ is ejected from the compact star with its specific orbital angular momentum.

For 2 million yrs, transfer rate > 10^{-7} Msun/yr

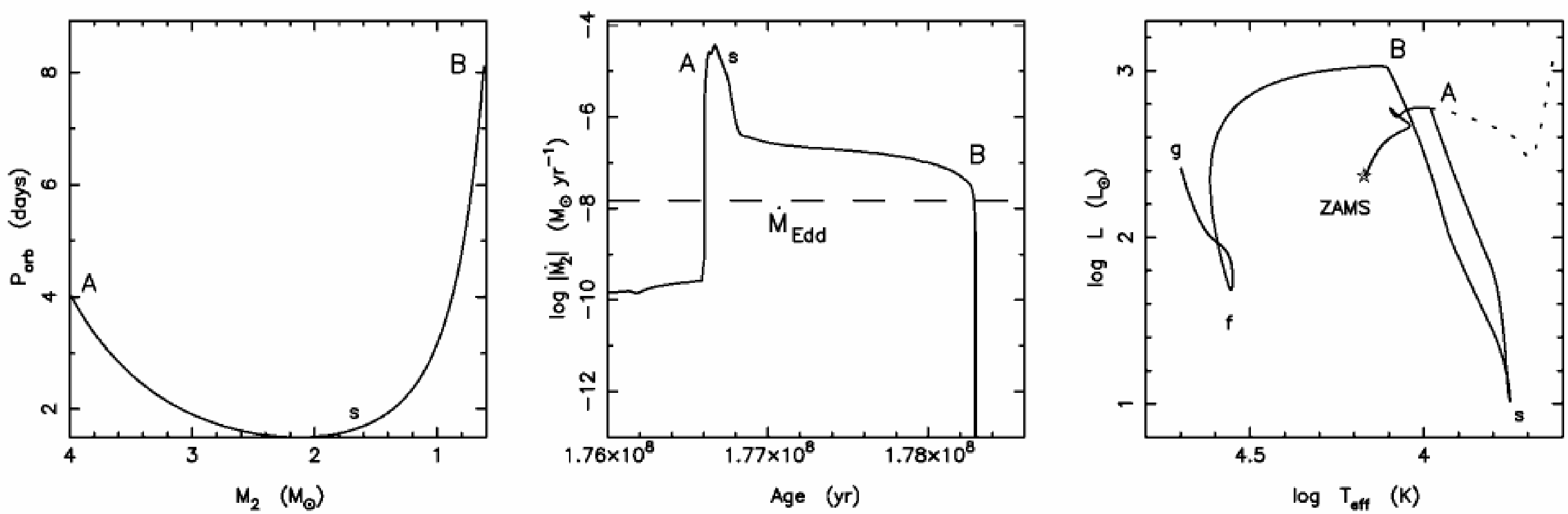


FIG. 1.—Evolution of an X-ray binary with $M_2 = 4.0\ M_\odot$ and $P_{orb} = 4.0$ days. *Left:* Evolution of P_{orb} as a function of M_2 (time is increasing to the right). *Middle:* Mass-loss rate of the donor as a function of its age since the ZAMS. *Right:* Evolution of the mass-losing donor (*solid line*) in an H-R diagram. The dotted line represents the evolutionary track of a single 4.0 $M_\odot$ star. The letters in the different panels correspond to one another at a given evolutionary epoch—see text for further explanation.

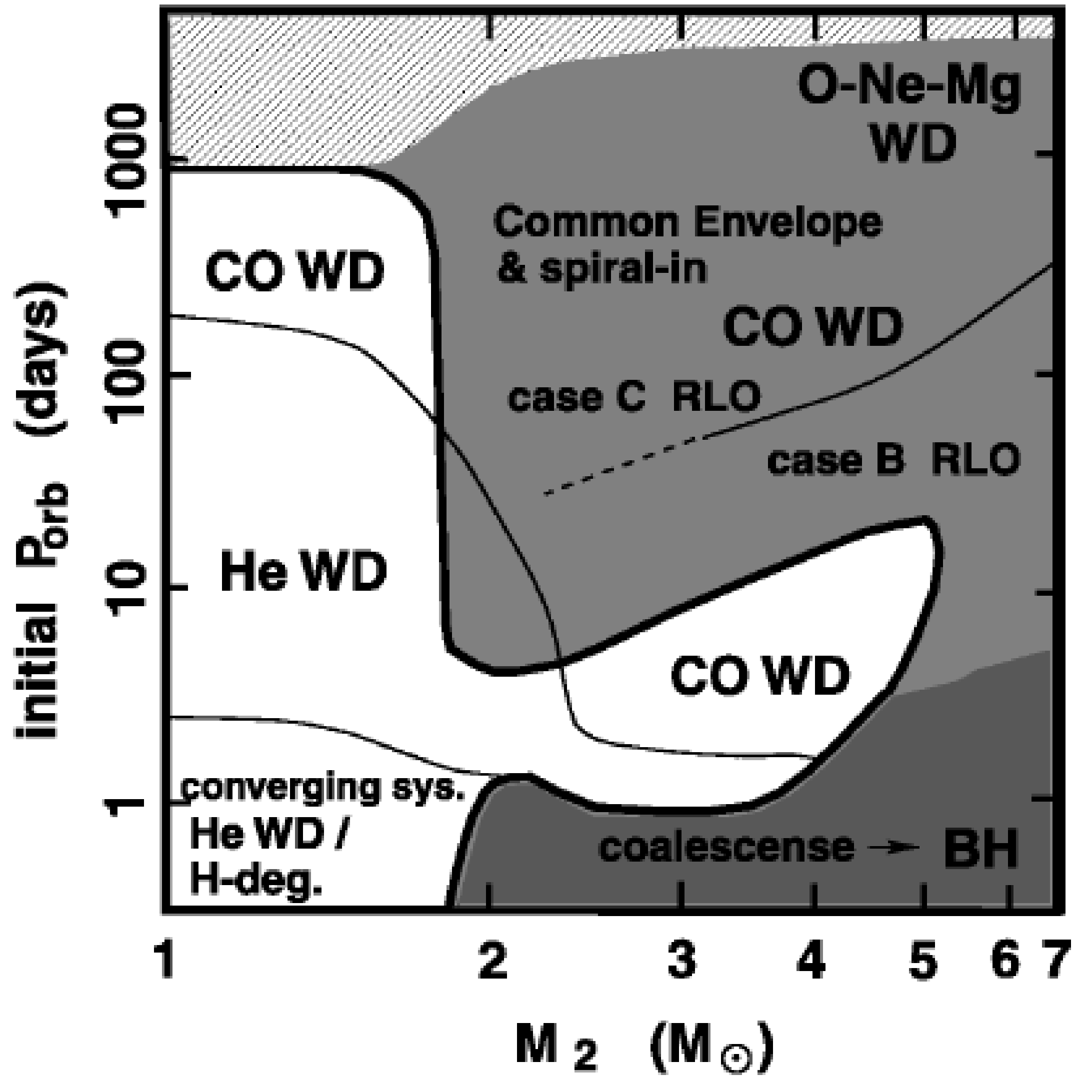


FIG. 4.—Allowed parameter space (*white area*) for producing BMSPs without evolving through a CE phase. If $M_2 > 1.8\ M_\odot$ and the donor has a deep convective envelope at the onset of mass transfer (i.e., P_{orb} is large), the system will evolve into a CE and spiral-in phase. This is also the case if the initial period is very short and $M_2 > 1.8\ M_\odot$. In the latter case the neutron star may collapse into a black hole.

Conclusions:

-With companions of ~ $1M_{sun}$ in narrow as well as wide orbits mass transfer rates of order > 10^{-8} M_{sun}/yr can be driven for long times (~10 to 50 million yrs), such that – if this mass can be retained – the WD can grow substantially in mass (0.1 – $0.6M_{sun}$).

-With thermal timescale mass transfer from > 1.5 M_{sun} up to ~ $5M_{sun}$ companions,mass accretion rates > 10^{-7} M_{sun}/yr can be sustained for several million yrs, allowing the WDs to grow with > 0.1 to 0.2 solar masses.

-Precise Population synthesis calculations of all these different scenarios will be required in order to see whether, all combined, can meet the observed SN Ia rate.