Tracing non-conservative mass transfer eras in close binaries from observed period variations

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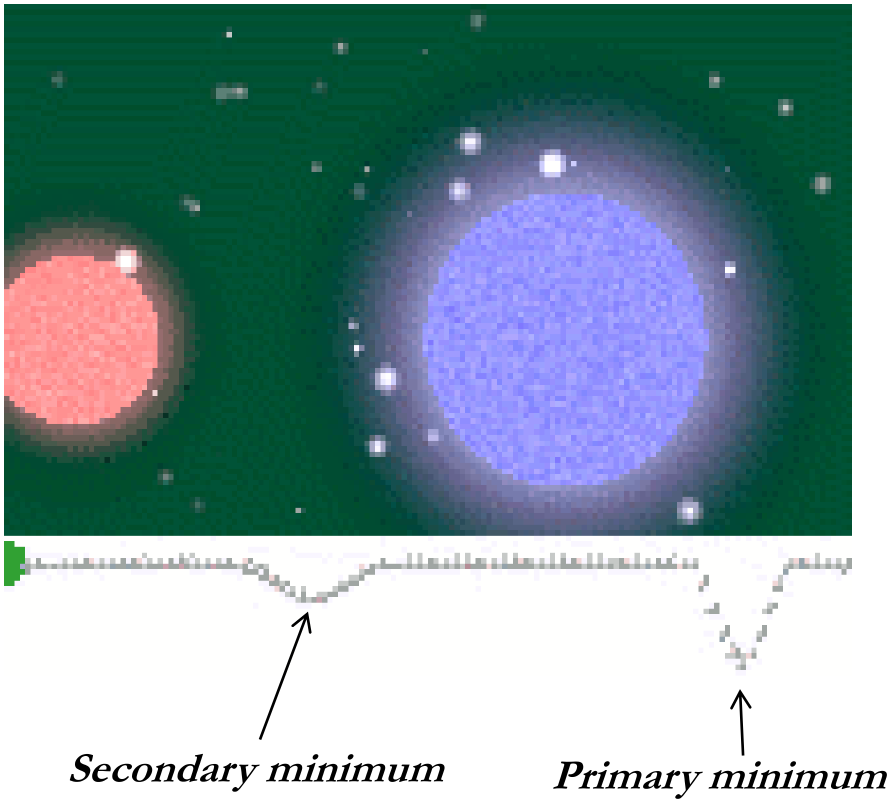
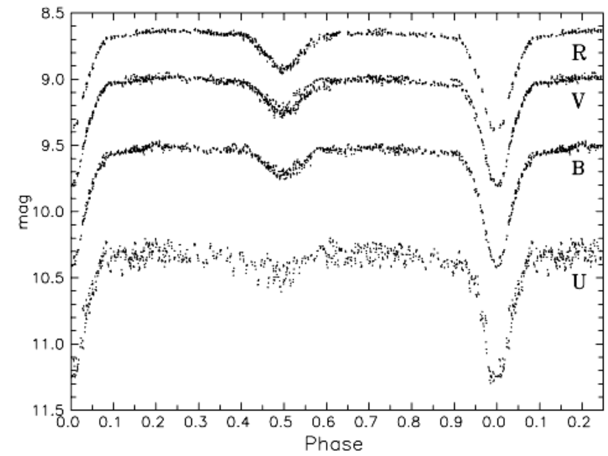
Eclipsing Binaries



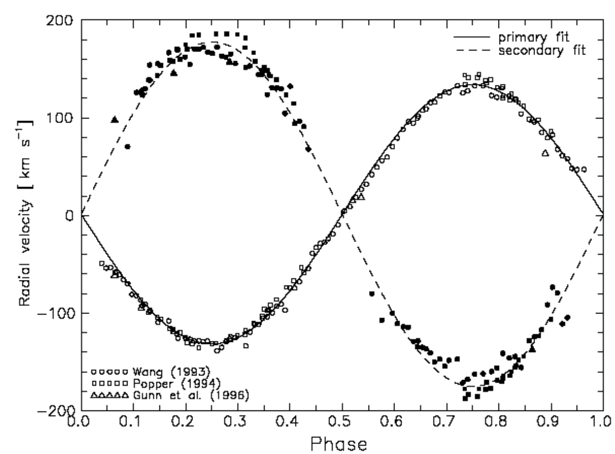
Accurate determination of
orbital / physical parameters:

P*, *i*, *q*, *T*, *L*, *M*, *R*, log*g

Light Curve



R. Velocities Curve



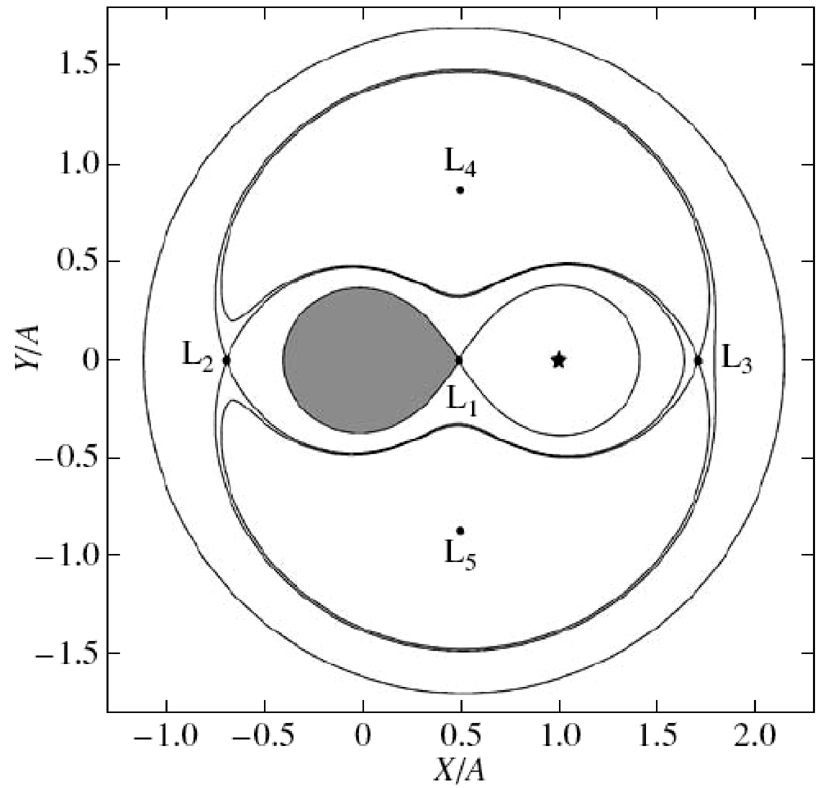
RT And (Pribulla et al. 2000)

Roche geometry
- Classification -

Roche lobes: inner equipotential surface

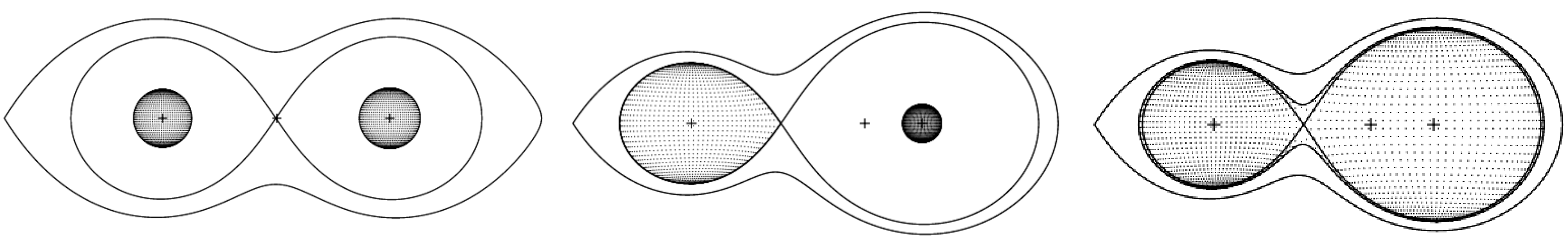
Lagrangian points: lowest potential barriers

L1: mass transfer
L2: mass loss (donor, the more massive)
L3: mass loss (donor, the less massive)



***q* = 0.93** (Sytov et al. 2007)

Detached **Semi-detached** **Contact**



O-C diagrams (Eclipse Timing Variations)

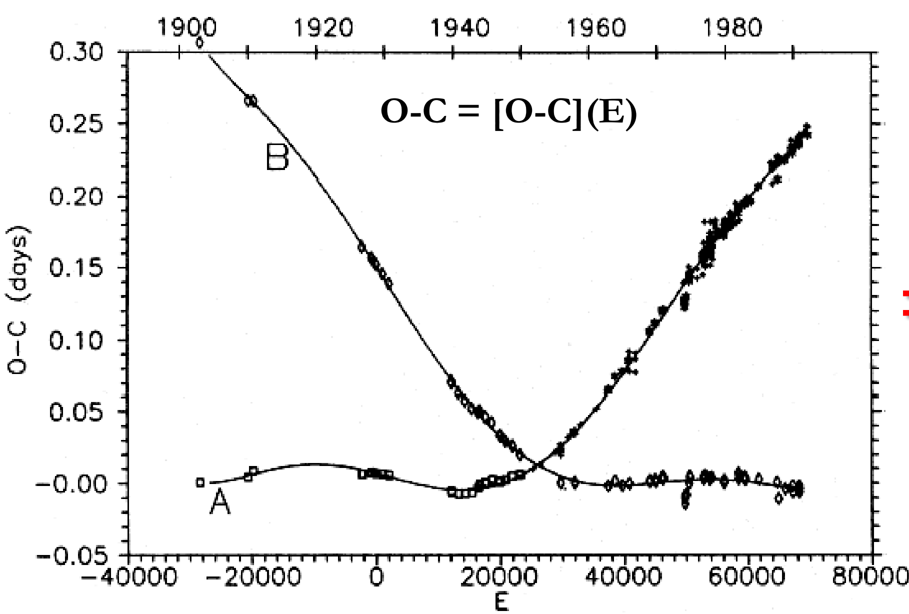
- **C**alculated times of minima: C(E) = $\boxed{T_0 + P_e E}$
- **O**bserved times of minima: O(E)

linear ephemeris (T_0,P_e)

integer orbital cycle E

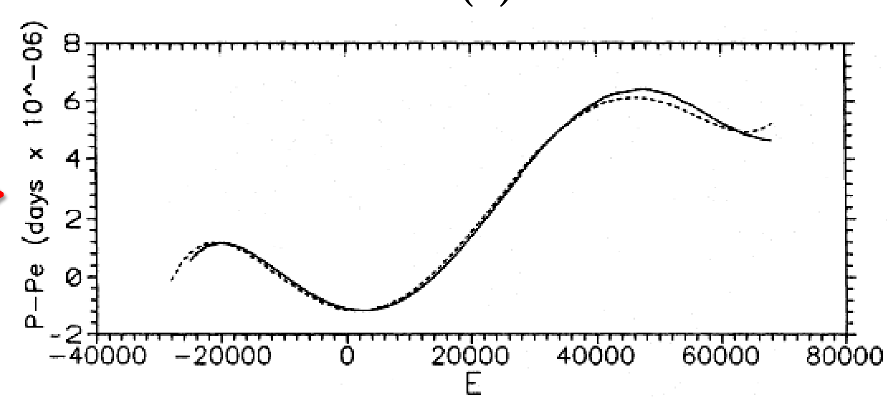
O(E)-C(E) differences ⇒ O-C diagrams

if ΔT(E) represents an O-C diagram ⇒ Period diagram: $P(E) = P_e + \Delta T(E) - \Delta T(E\text{-}1)$



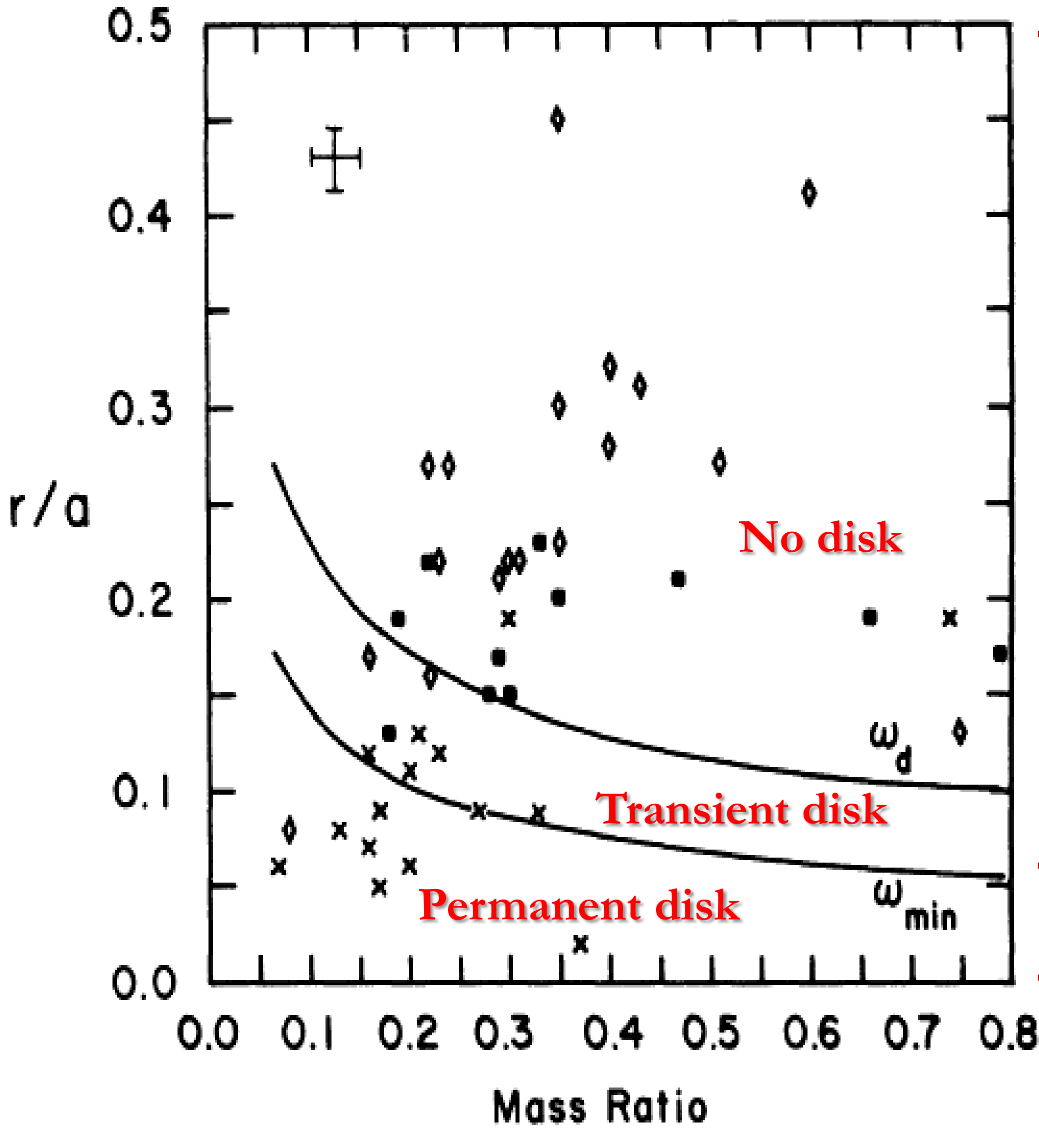
⇒

P = P(E)



AB And (Kalimeris et al. 1994)

Conservative mass transfer: Modes



r-q diagram (Kaitchuck et al. 1985)

Critical gainer's radius

$$\omega_d = \omega_d(q)$$

$$\omega_{min} = \omega_{min}(q)$$

(Lubow & Shu 1975)

Direct impact mode

Accretion disk mode

Conservative mass transfer

All the transferred mass is captured by the gainer !

M_1: mass of the primary component, M_2: mass of the secondary component

$q = M_2/M_1 \leq 1$: mass ratio of the system, r_r : disk radius (dimensionless)

$r_r = r_r(q)$ (Lubow & Shu 1975, Verbunt & Rappaport 1988)

Donor	**No disk**	**Transient disk**
Primary component	$\frac{\dot{P}}{P} = -3(1-q)\frac{\dot{M}_2}{M_2} < 0$	$\frac{\dot{P}}{P} = -3\left[1-q+\boxed{\sqrt{q(q+1)r_r}}\right]\frac{\dot{M}_2}{M_2} < 0$
Secondary component	$\frac{\dot{P}}{P} = -3(q-1)\frac{\dot{M}_1}{M_2} > 0$	$\frac{\dot{P}}{P} = -3\left[q-1+\boxed{\sqrt{(q+1)r_r}}\right]\frac{\dot{M}_1}{M_2}$

$q < q_{cr} = 0.59$: the period increases, $q > q_{cr} = 0.59$: the period decreases !!!

Non-conservative mass transfer: Paths

Hot spot (re-)emission

Why a hot spot ?

the gaseous flow stream trajectories tend to converge on landing points of the gainer, localized in a rather small region compared to the overall star surface (Kruszewski 1964)

Why (re-)emission ?

the radiative energy a hot spot is strengthened due to the limited accreted zone and, along with the rotational kinetic energy, surmounts the gravitational binding energy. The system is subject to a liberal era, expected soon after the onset of the RLOF phase (van Rensbergen et al. 2008)

Mass loss via the L2/L3 points

Why via L2/L3 ?

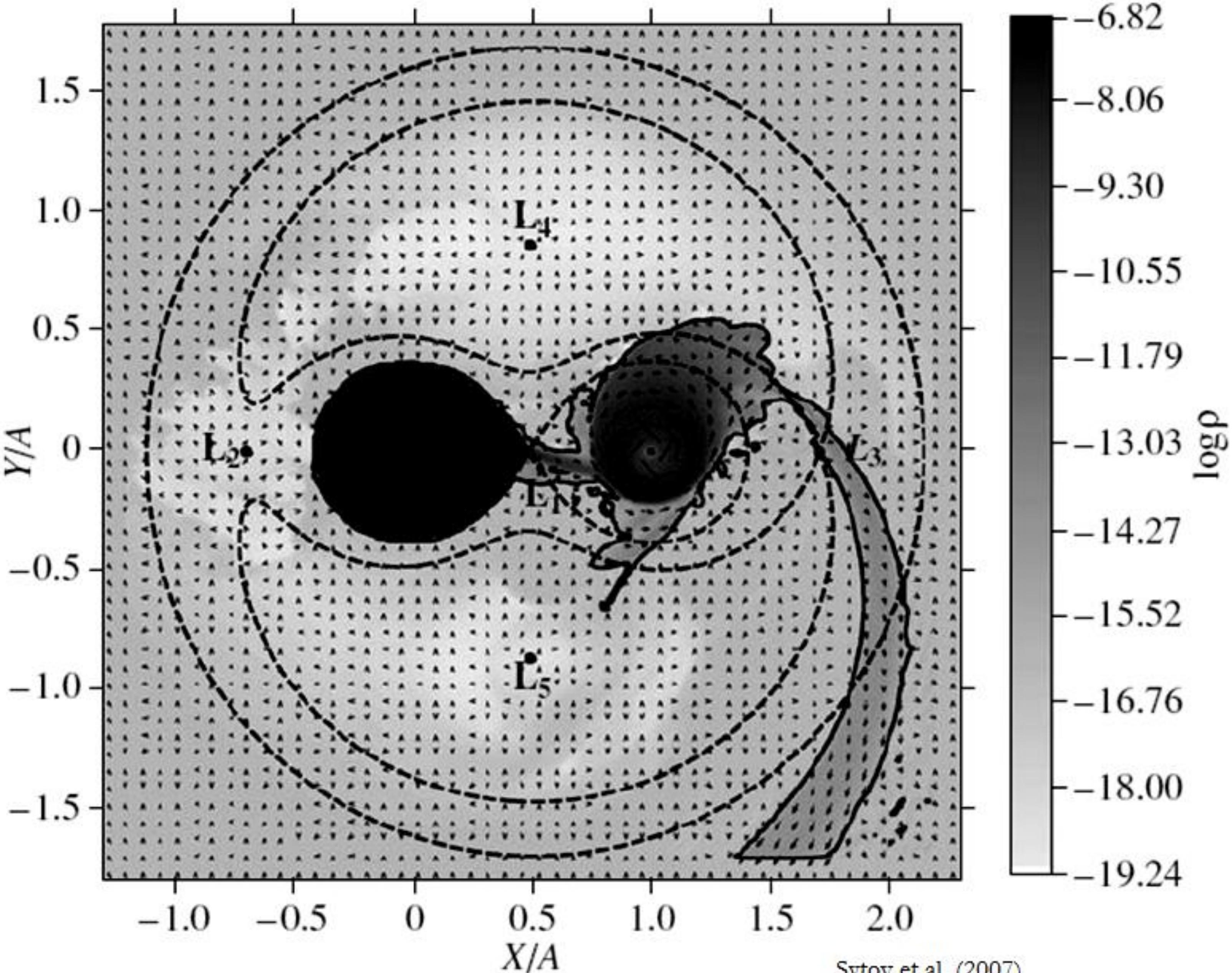
They are paths that matter can escape most easily from the gravitational field of the binary, demanding the lowest energy than elsewhere. A circumbinary disk can form in this way (Shu et al. 1979, Sytov et al. 2007, Basikalo 2010, Mennickent et al. 2012a,b).

via L2: primary component as the donor

via L3: secondary component as the donor

AML through L2/L3 >> AML through a hot spot

Non-conservative mass transfer: Paths



Sytov et al. (2007)

Non-conservative mass transfer: Hot spot re-emission

All the transferred mass is re-emitted by the gainer !

M_1: mass of the primary component, M_2: mass of the secondary component

m_{hs}: mass lost from the system, j_{hs} : stream's specific angular momentum

$j_{hs} = j_{hs}(q)$ (de Mink et al. 2007, van Rensbergen et al. 2011)

Donor

Primary component

$$\frac{\dot{P}}{P} = \left[\boxed{-\frac{3q+2}{M_1+M_2}} + \boxed{\frac{3(1+q)}{M_2} j_{hs}} \right] \dot{m}_{hs}$$

Secondary component

$$\frac{\dot{P}}{P} = \left[\boxed{-\frac{3q^{-1}+2}{M_1+M_2}} + \boxed{\frac{3(1+q)}{M_2} j_{hs}} \right] \dot{m}_{hs} > 0$$

$\boxed{q < q_{cr} = 0.72\text{: the period decreases, } q > q_{cr} = 0.72\text{: the period increases !!!}}$

Non-conservative mass transfer: Mass loss via L2/L3

All the transferred mass is rejected by the gainer !

M_1: mass of the primary component, M_2: mass of the secondary component

$m_{L2/L3}$: mass lost from the system, $j_{L2/L3}$: stream's specific angular momentum

$j_{L2/L3} = j_{L2/L3}(q)$ (Shu et al. 1979, Nanouris et al. 2013)

Donor

Primary component

$$\frac{\dot{P}}{P} = \left[-\frac{3q+2}{M_1+M_2} + \frac{3(1+q)}{M_2} j_{L2} \right] \dot{m}_{L2} < 0$$

Secondary component

$$\frac{\dot{P}}{P} = \left[-\frac{3q^{-1}+2}{M_1+M_2} + \frac{3(1+q)}{M_2} j_{L3} \right] \dot{m}_{L3} < 0$$

$\boxed{\text{the period decreases for any } q \text{ !!!}}$

Non-conservative mass transfer: Primary as the donor

Part of the transferred mass is re-emitted/rejected by the secondary !

β: degree of liberalism ($\beta = 1$: fully conservative case, $\beta = 0$: fully liberal case)

$\dot{M}_2 = -\beta \dot{M}_1$: mass captured by the secondary, $\dot{m} = (1-\beta)\dot{M}_1$: mass escaped from the system

ML through a hot spot			ML through the L2 point	
β (liberalism)	q_{cr} (for $r_r = 0$)	q_{cr} (for $r_r \neq 0$)	q_{cr} (for $r_r = 0$)	q_{cr} (for $r_r \neq 0$)
0.0	**0.721**	**0.721**	-	-
0.1	0.744	0.774	-	-
0.2	0.768	0.833	-	-
0.3	0.793	0.897	-	-
0.4	0.820	0.968	-	-
0.5	0.847	-	-	-
0.6	0.876	-	-	-
0.7	0.905	-	-	-
0.8	0.936	-	-	-
0.9	0.967	-	-	-
1.0	**1.000**	-	1.000	-

Binaries with mass ratio q greater than the listed q_{cr} values will reveal an increasing period (and a convex O−C diagram) !!!

Non-conservative mass transfer: Secondary as the donor

Part of the transferred mass is re-emitted/rejected by the primary !

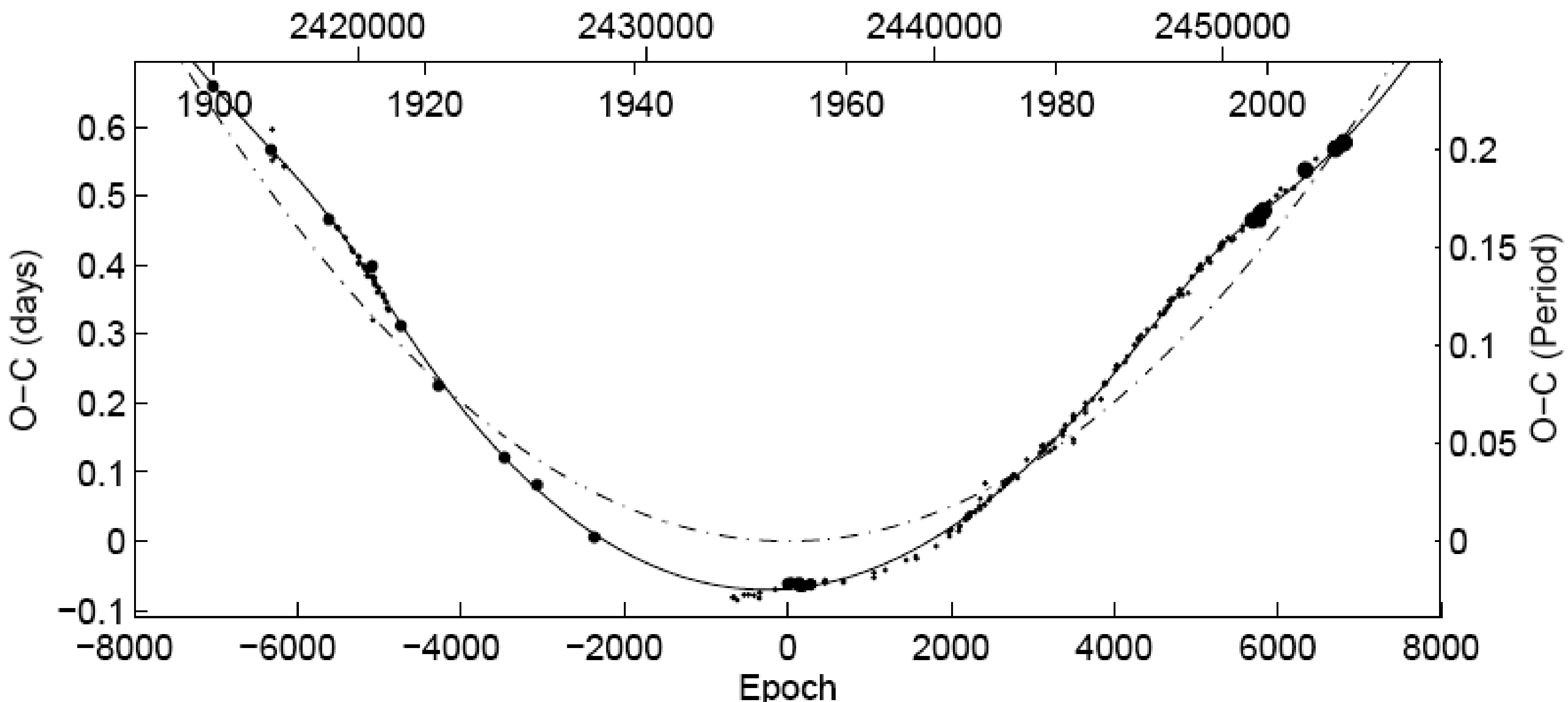
β: degree of liberalism ($\beta = 1$: fully conservative case, $\beta = 0$: fully liberal case)

$\dot{M}_1 = -\beta \dot{M}_2$: mass captured by the secondary, $\dot{m} = (1-\beta)\dot{M}_2$: mass escaped from the system

ML through a hot spot			ML through the L3 point	
β (liberalism)	q_{cr} (for $r_r = 0$)	q_{cr} (for $r_r \neq 0$)	q_{cr} (for $r_r = 0$)	q_{cr} (for $r_r \neq 0$)
0.0	-	-	-	-
0.1	-	-	0.047	0.011
0.2	-	-	0.104	0.041
0.3	-	-	0.168	0.078
0.4	-	-	0.240	0.121
0.5	-	0.954	0.322	0.172
0.6	-	0.876	0.417	0.231
0.7	-	0.801	0.527	0.300
0.8	-	0.728	0.657	0.381
0.9	-	0.659	0.813	0.477
1.0	**1.000**	**0.591**	**1.000**	**0.591**

Binaries with mass ratio q greater than the listed q_{cr} values will reveal a decreasing period (and a concave O−C diagram) !!!

Case study 1: RR Dra



Zasche et al. (2008)

Semi-detached binary (donor: secondary, O-C diagram: convex)

$\mathbf{M_1} = 2.15\ M_\odot$, $\mathbf{M_2} = 0.6\ M_\odot$, $\boldsymbol{q} = 0.279$ (Svechnikov & Kuznetsova 1990)

$\mathbf{P} = 2.8312$ d, $\mathbf{dP/dt} = +8.9079 \times 10^{-9}$ (Zasche et al. 2008)

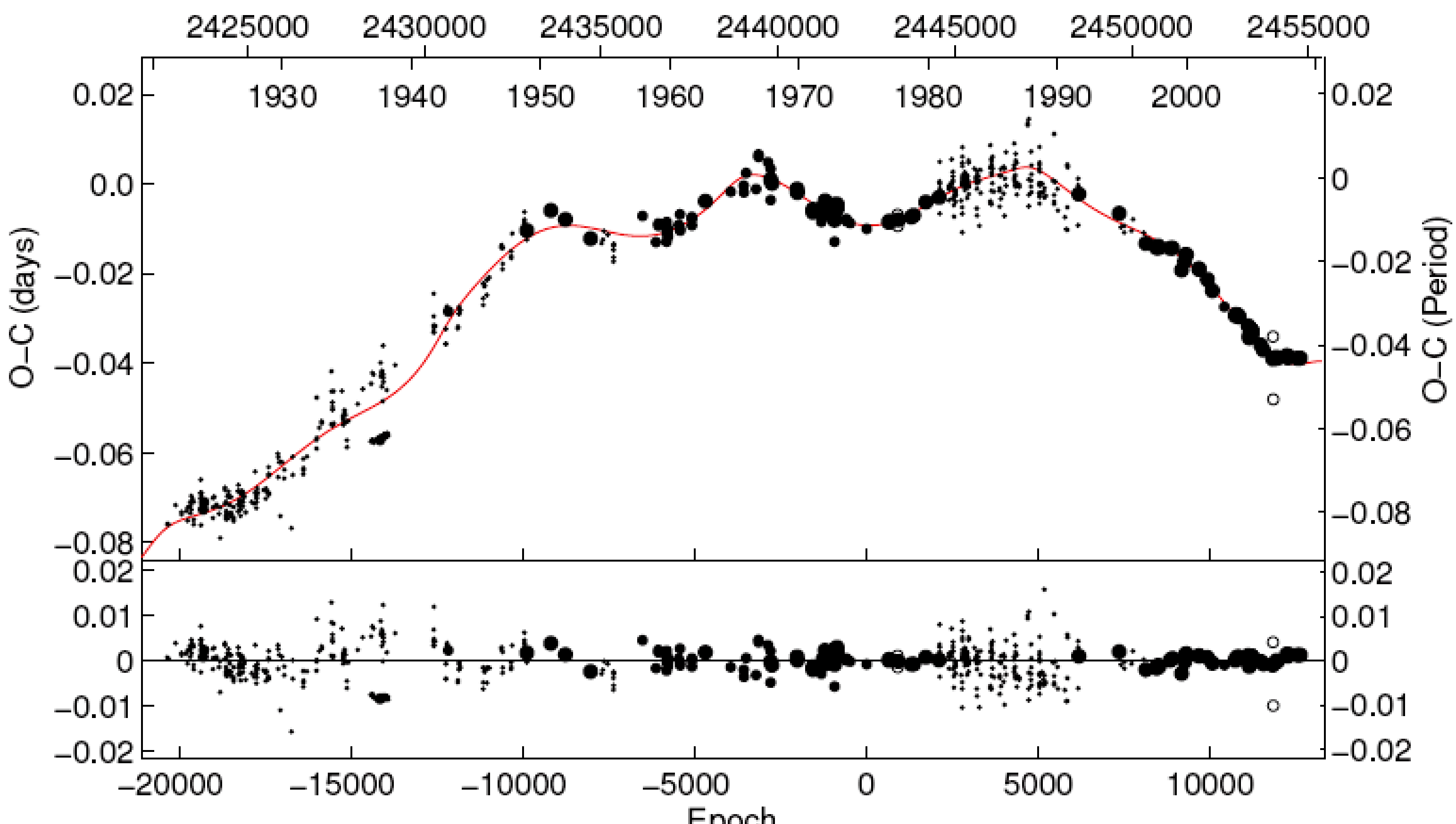
Evidence for a transient disk (Kaitchuck et al. 1985)

Case study 1: RR Dra

ML through a hot spot			ML through the L3 point	
β (degree of liberalism)	**dM_1/dt** $[M_\odot/yr]$ (for $r_r \neq 0$)	**dm/dt** $[M_\odot/yr]$ (for $r_r \neq 0$)	**dM_1/dt** $[M_\odot/yr]$ (for $r_r \neq 0$)	**dm/dt** $[M_\odot/yr]$ (for $r_r \neq 0$)
0.0	0.00	-2.64×10^{-07}	-	-
0.1	2.84×10^{-08}	-2.56×10^{-07}	-	-
0.2	6.12×10^{-08}	-2.45×10^{-07}	-	-
0.3	9.95×10^{-08}	-2.32×10^{-07}	-	-
0.4	1.45×10^{-07}	-2.17×10^{-07}	-	-
0.5	1.99×10^{-07}	-1.99×10^{-07}	-	-
0.6	2.66×10^{-07}	-1.77×10^{-07}	-	-
0.7	3.49×10^{-07}	-1.50×10^{-07}	6.49×10^{-06}	-2.78×10^{-06}
0.8	4.56×10^{-07}	-1.14×10^{-07}	1.64×10^{-06}	-4.09×10^{-07}
0.9	5.99×10^{-07}	-6.66×10^{-08}	1.04×10^{-06}	-1.15×10^{-07}
1.0	8.00×10^{-07}	0.00	8.00×10^{-07}	0.00

Conservative case without disk: **dM_1/dt** $= 3.2\times10^{-7}\ M_\odot/yr$ (Zasche et al. 2008)

Case study 2: X Tri



Liakos et al. (2010)

Semi-detached binary (donor: secondary, O-C diagram: concave)

$\mathbf{M_1} = 2.3\ M_\odot$, $\mathbf{M_2} = 1.2\ M_\odot$, $\boldsymbol{q} = 0.522$ (Mezzetti et al. 1980)

$\mathbf{P} = 0.9715$ d, $\mathbf{dP/dt} = -1.5269 \times 10^{-10}$ (Liakos et al. 2010)

Case study 2: X Tri

ML through the L3 point				
β (degree of liberalism)	**dM_1/dt** [$M_\odot$/yr] (for $r_r = 0$)	**dm/dt** [$M_\odot$/yr] (for $r_r = 0$)	**dM_1/dt** [$M_\odot$/yr] (for $r_r \neq 0$)	**dm/dt** [$M_\odot$/yr] (for $r_r \neq 0$)
0.0	0.00	-2.15×10^{-08}	0.00	-2.10×10^{-08}
0.1	2.45×10^{-09}	-2.21×10^{-08}	2.35×10^{-09}	-2.11×10^{-08}
0.2	5.89×10^{-09}	-2.36×10^{-08}	5.33×10^{-09}	-2.13×10^{-08}
0.3	1.11×10^{-08}	-2.58×10^{-08}	9.24×10^{-09}	-2.16×10^{-08}
0.4	1.98×10^{-08}	-2.96×10^{-08}	1.46×10^{-08}	-2.19×10^{-08}
0.5	3.73×10^{-08}	-3.73×10^{-08}	2.24×10^{-08}	-2.24×10^{-08}
0.6	9.14×10^{-08}	-6.10×10^{-08}	3.47×10^{-08}	-2.31×10^{-08}
0.7	-	-	5.72×10^{-08}	-2.45×10^{-08}
0.8	-	-	1.12×10^{-07}	-2.79×10^{-08}
0.9	-	-	4.25×10^{-07}	-4.72×10^{-08}
1.0	-	-	-	-

Concluding remarks

Both the presence of a transient disk and a possible non-conservative mass transfer status are able to change considerably the monotony of the period variations and the morphology of the respective O-C diagrams.

Critical mass ratios may arise for a certain degree of liberalism !

But… the simplistic β-q schemes seem to be insufficient in describing the short orbital evolution of a binary in which MT is not the leading orbital period evolutionary mechanism.

Efficiency of O-C diagrams as diagnostic tools for long-term period variations.

II. Non-conservative mass transfer and gravitational radiation

Nanouris N., Kalimeris A., Antonopoulou E., Rovithis-Livaniou H.

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