Modeling of the long and short timescales in the evolution of a close binary system containing a radio pulsar

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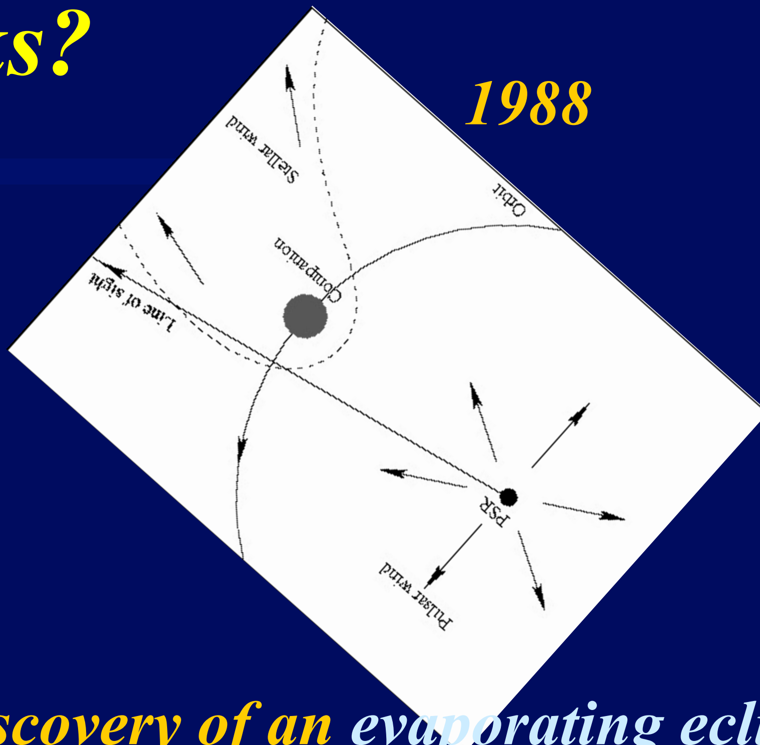
What black widows and redbacks?

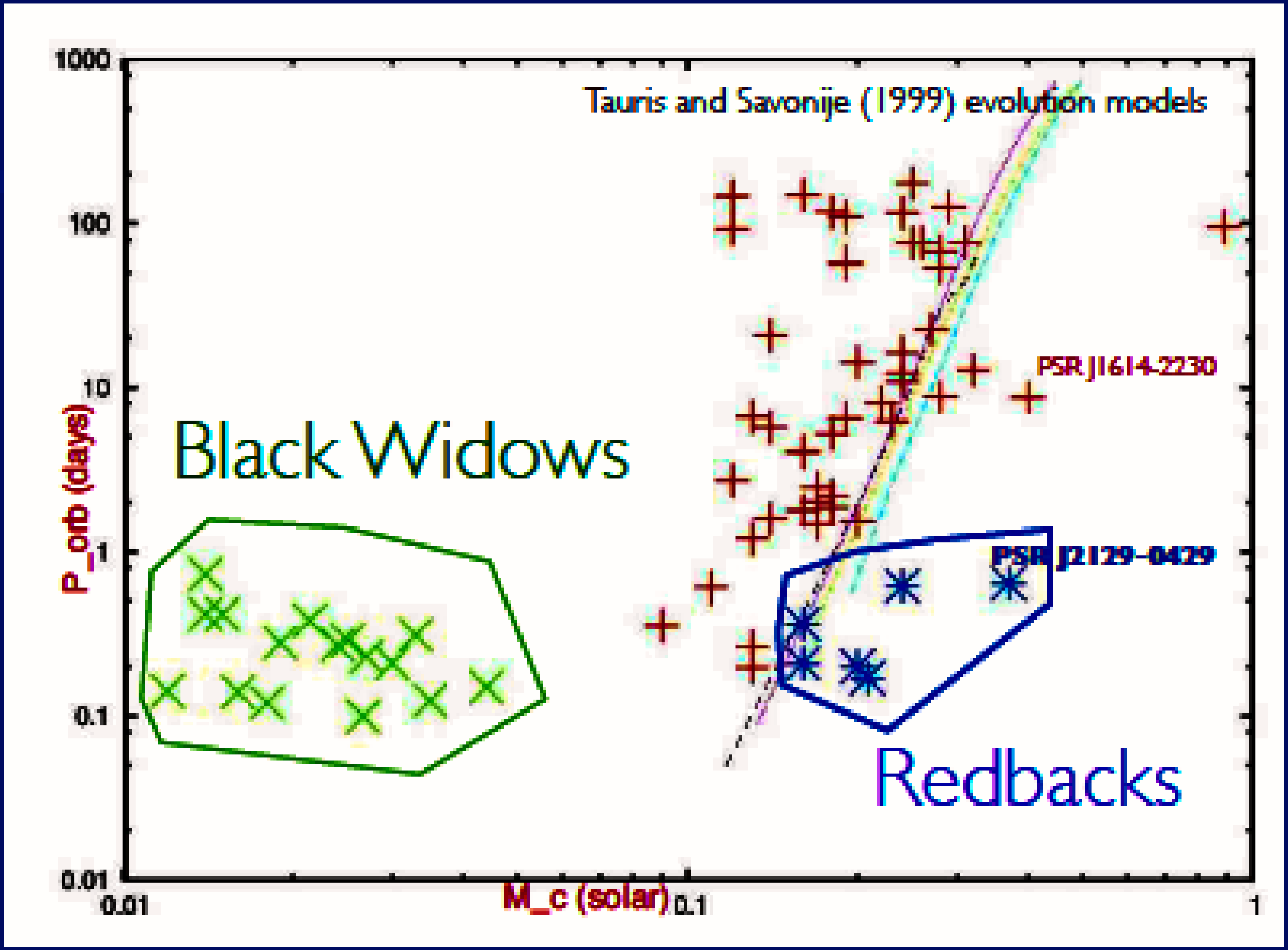
1988



Chandra and Hubble (2001)

1988: discovery of an evaporating eclipsing system PSR 1957+20: irradiated surface by a recycled PSR, mass loss of the donor to the ISM (comet-like effect)

Later, the australians discovered similar systems but in which there is no evaporation: because of their parenthood they named them "redbacks" (an australian spider…)



M. Roberts, arXiv:1210.6903

Evolution models

Simultaneous solving of orbit + stellar structure equations (Henyey)

Accretion from donor M_1 → $\dot{M}_1 = -\beta \dot{M}_2$ **a fraction** β **captured by the neutron star M_2 (assumed fixed)**

In general, $\beta < 1$ **and angular momentum is lost from the system. The exact value of** β **is not critical**

Evaporating wind

$$\dot{M}_{2,evap} = -\frac{f}{2v_{2,esc}^2} L_P \left(\frac{R_2}{a}\right)^2$$

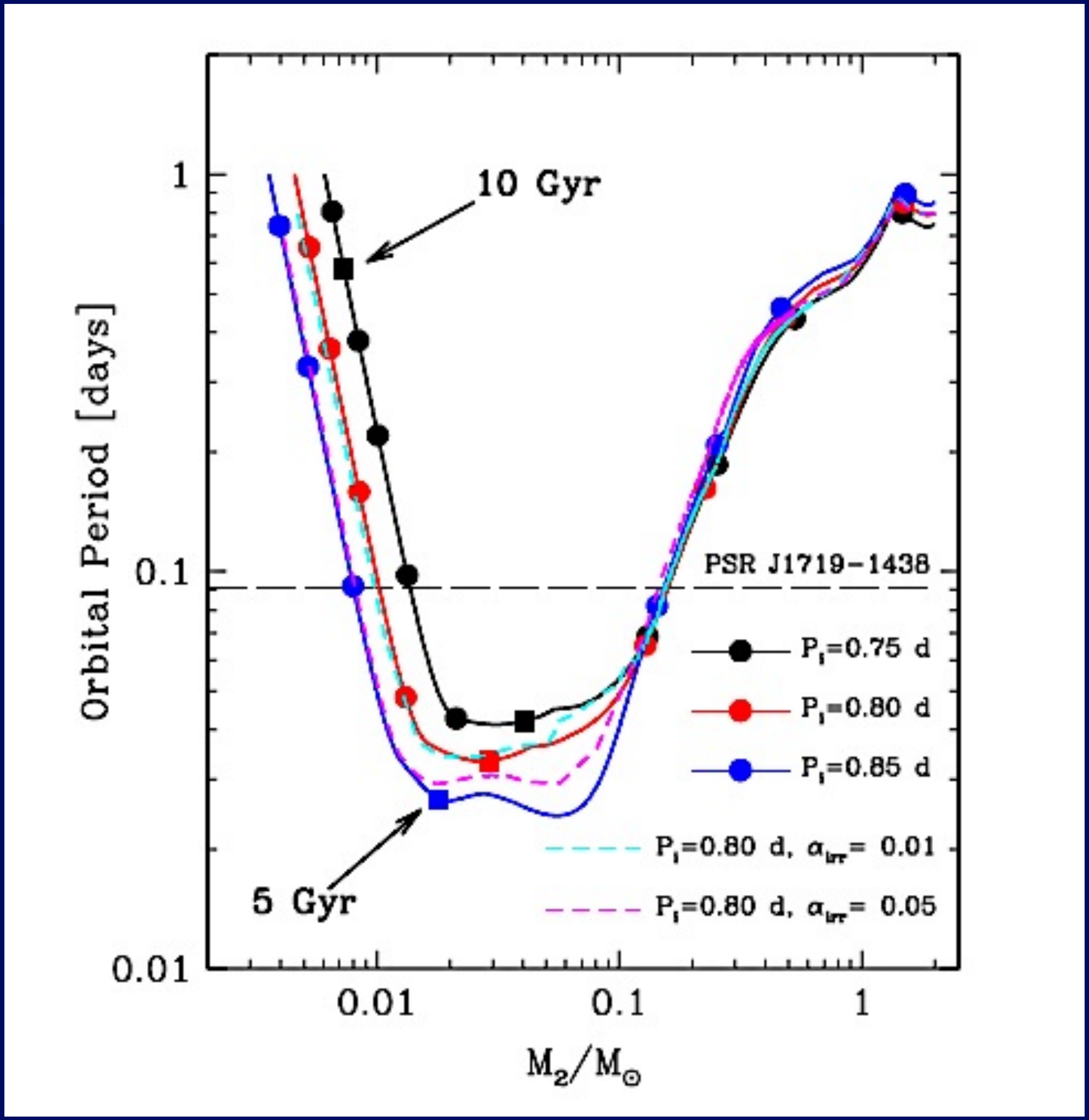
1st ingredient
(Stevens et al., MNRAS 254, 19, 1992)

with $L_P = 4\pi^2 I_1 P_1^{-3} \dot{P}_1$

Irradiation feedback

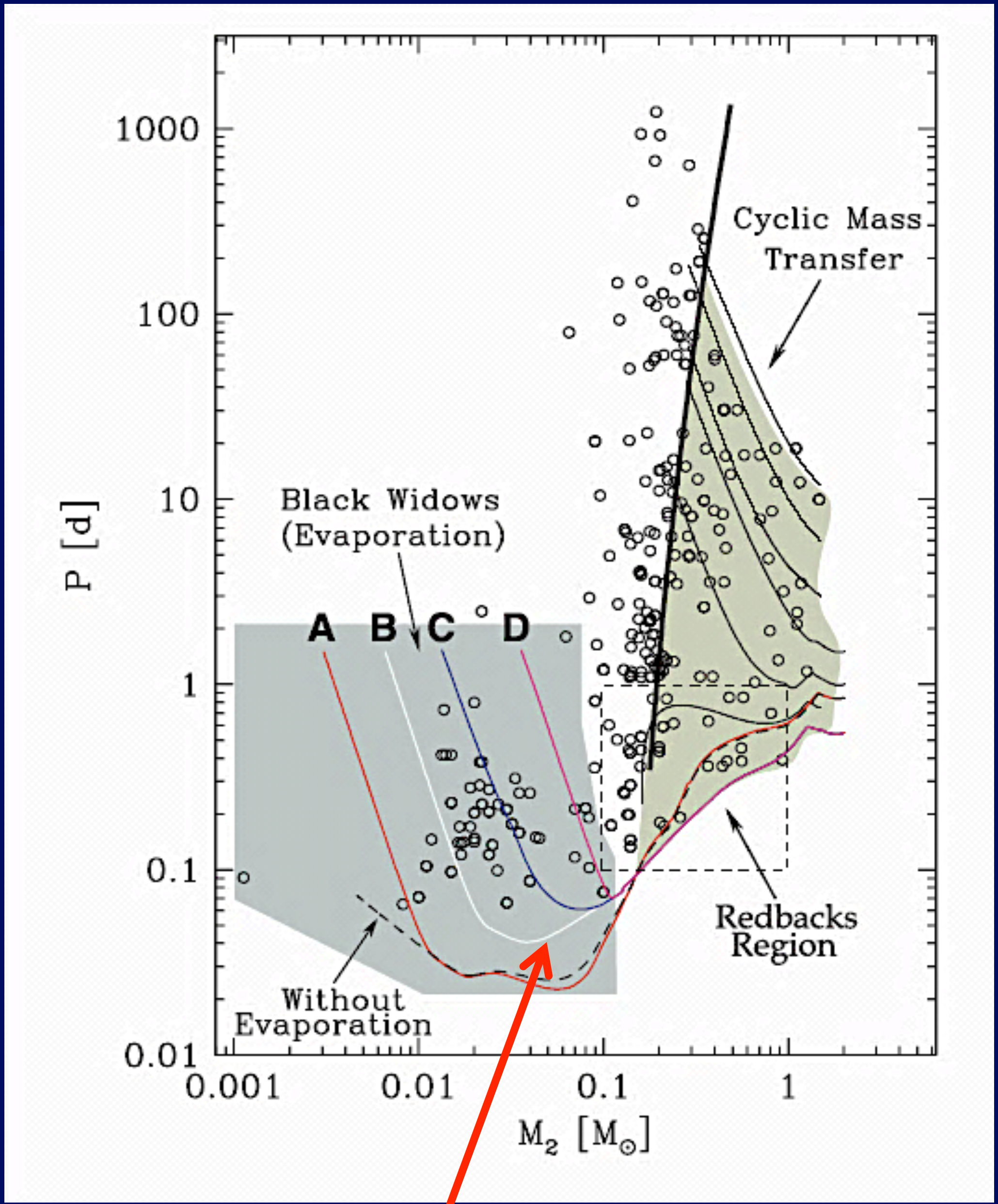
$$F_{irr} = \frac{\alpha_{irr}}{4\pi a^2} \frac{G M_1}{R_1} \dot{M}_1$$

2nd ingredient
(Bunning & Ritter, A&A 423, 281, 2004 Hameury)



Benvenuto, De Vito & Horvath, ApJLett 753, L33, 2012

Calculations



Donors become degenerate here

Evolutionary tracks starting at short periods, giving rise to "redbacks" and later to "black widow" systems

Track A: $P_i = 0.85$ days, $\alpha_{evap} L_{PSR} = 0.04\ L_\odot$

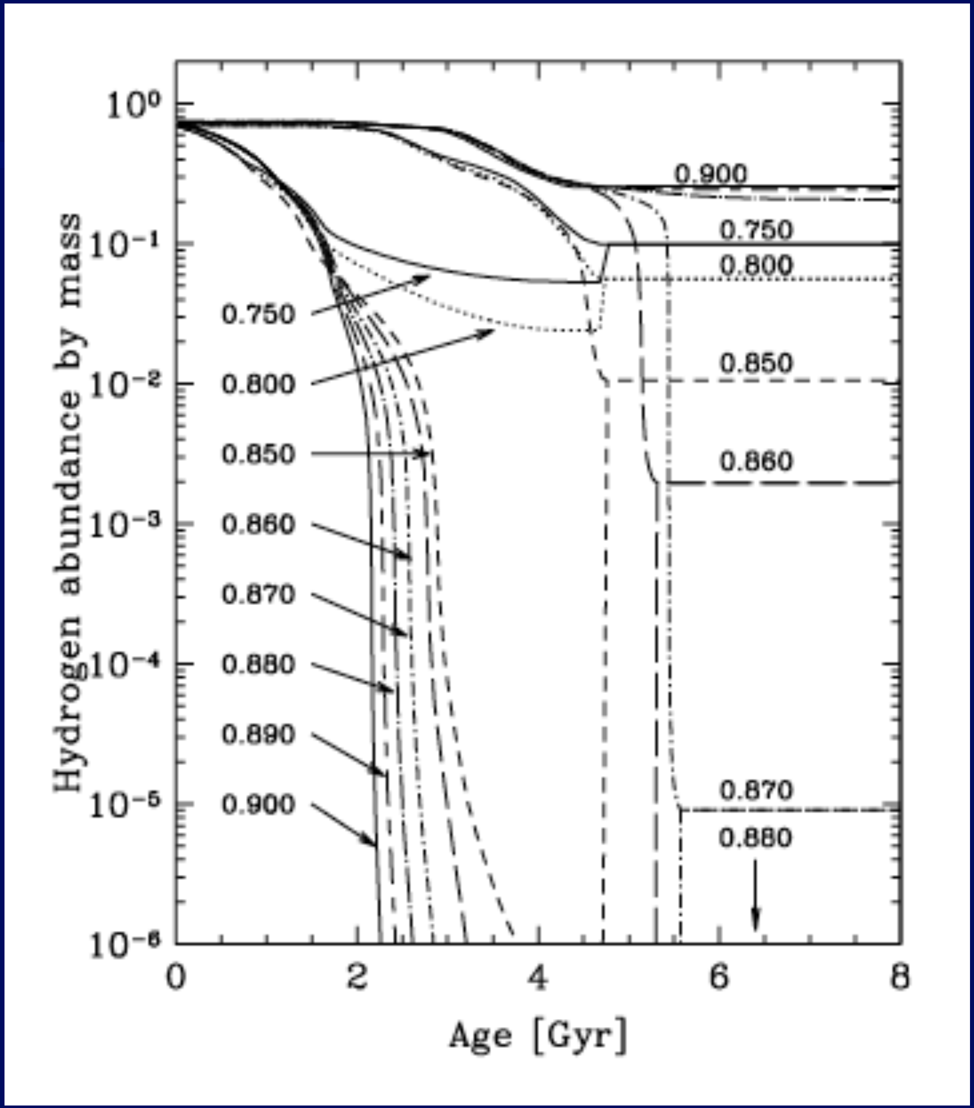
Track B: $P_i = 0.55$ days, $\alpha_{evap} L_{PSR} = 0.04\ L_\odot$

Track C: $P_i = 0.55$ days, $\alpha_{evap} L_{PSR} = 0.20\ L_\odot$

Track D: $P_i = 0.55$ days, $\alpha_{evap} L_{PSR} = 1.00\ L_\odot$

If the starting period is longer, the system detaches and goes up

"Tidarren spiders" like PSR J1311- 3430 a special case



It is enough that the initial period is sufficiently long to allow the hydrogen abundance in the core

$$X_c^{RLOF} = 0$$

when the donor becomes completely convective

Benvenuto, De Vito & Horvath, MNRAS 433, L11, 2013

The quasi-RLOF state in redbacks

X-ray irradiation feedback from the accretion is seldom considered in stellar binaries, but it is important for these systems. The flow of energy from the interior is partially blocked and produces a cyclic mass transfer behavior. The usual expression for the luminosity of the donor

$$L = 4\pi R_2^2 \, \sigma \, T_{eff}^4$$

has to be replaced by

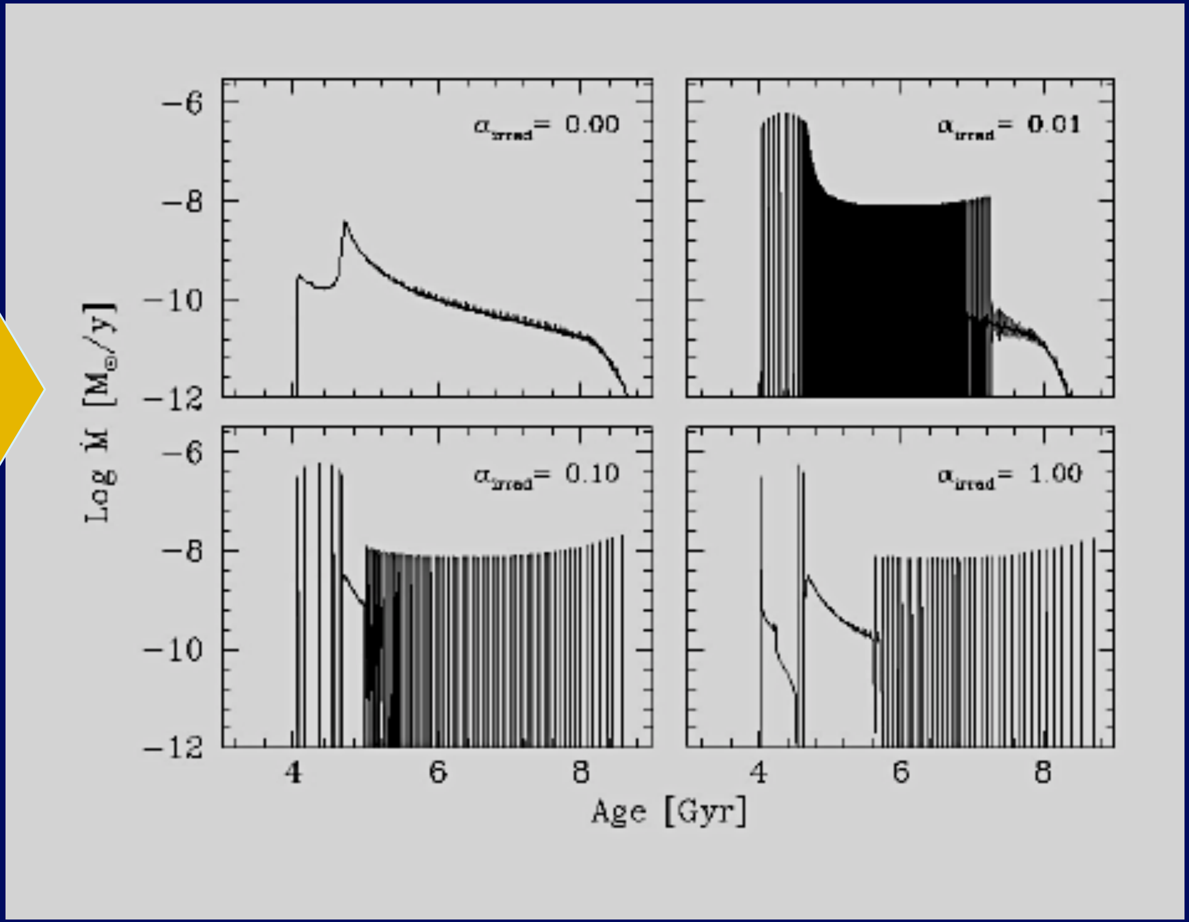
$$L = R_2^2 \, \sigma \, T_{eff,0}^4 \int_0^{2\pi} \int_0^{\pi} G(x(\theta,\phi)) \; \sin\theta \, d\theta \, d\phi,$$

with

$$G(x) = (T_{eff}(x)/T_{eff,0})^4 - F_{irr}/(\sigma \, T_{eff,0}^4)$$

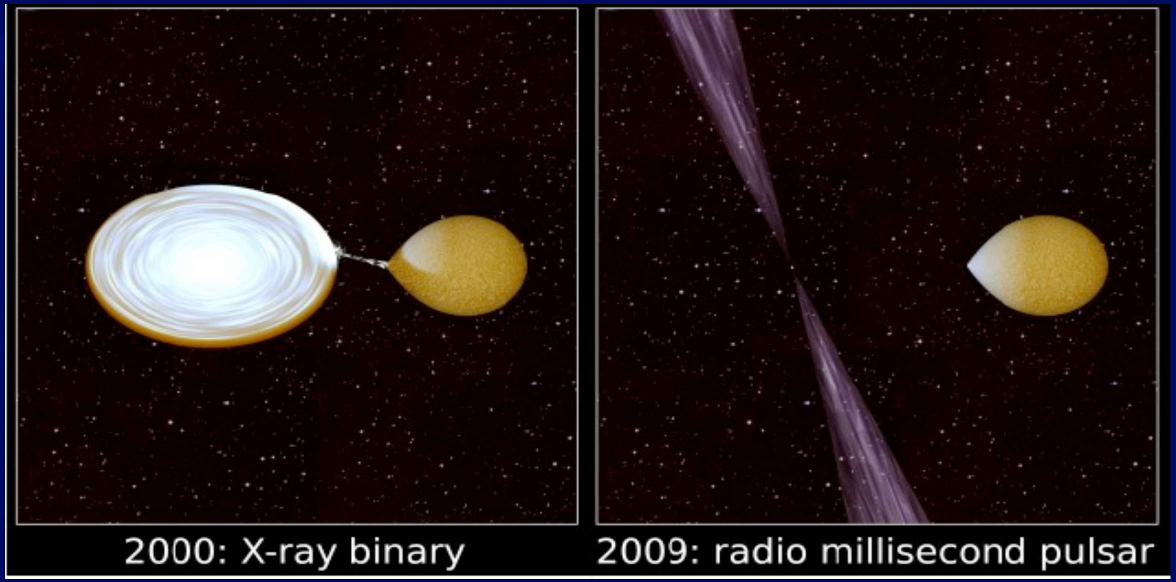
Since the quantity $F_{irr} = \alpha_{irr} L_{acc} / 4\pi a^2$ *depends on the irradiation strength* $\alpha_{irr} \leq 1$ *, we have calculated the mass transfer histories shown below for several values of this parameter*

From donor



Cycles last around ~1 Myr or more (controlled by nuclear timescale)

*Because of the X-ray irradiation, even when the systems **detach**, the radius of the solar-mass donor is **never** too different from the Roche Lobe Overflow value (donor swells)*



PSR J1023+0038

(from Roberts 2013)

This quase-RLOF timescale (~ 10^6 yr) is not the timescale for the disc destruction/rebuilding, driven by disc instabilities and operating for ~ few years. The back-and-forth switching of some tMSP (redbacks) has been confirmed recently.

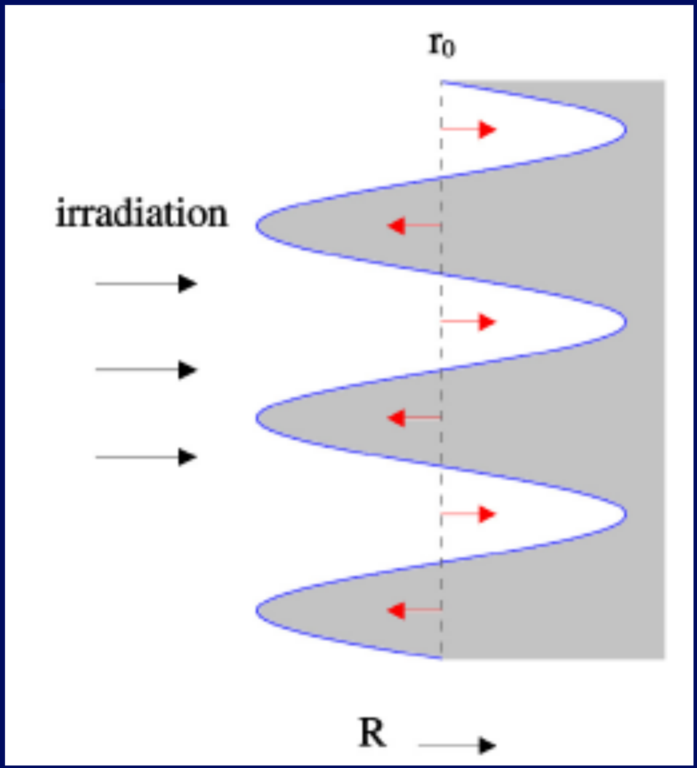
Evidence for the quasi-RLOF state : the filling factors

	Pulsar	P_s (ms)	T K	Filling Factor (kpc)	P_B (hrs)	M_{ns} (solar)
Old BWs	B1957+20[1] F	1.61	2500-5800	0.95	9.2	2.4
	J0610-2100[2] F	3.86	3500	High?	6.9	-
	J2051-0827[8]	4.51	2500-2800	0.43/0.95	2.4	
New BWs	J1311-3430[3] F	2.56	3440-12000	0.99	1.56	2.7
	J2241-5236 F	2.19			3.4	
	J2214+3000 F	3.12			10.0	
	J1745+1017 F	2.65			17.5	
	J2234+0944 F	3.63			10	
	J0023+0923[4] F	3.05	2900-4800	0.3	3.3	
	J1544+4937 F	2.16			2.8	
	J1446-4701 F	2.19			6.7	
	J1301+08 F	1.84			6.5	
	J1124-3653 F	2.41			5.4	
	J2256-1024[4] F	2.29	2450-4200	0.4	5.1	
	J2047+10 F	4.29			3.0	
	J1731-1847	2.34			7.5	
	J1810+1744[4] F	1.66	4600-8000	0.8	3.6	
New RBs	J1628-32 F	3.21			5.0	
	J1816+4510[5] F	3.19	15000	0.5	8.7	> 1.8
	J1023+0038[6] F	1.69	5600-6650	0.95	4.8	2.1
	J2215+5135[4] F	2.61	4800-6200	0.99	4.2	
	J1723-28	1.86			14.8	
	J2339-0533	2.88		high?	4.6	
	J2129-0429[7] F	7.61	5750	0.95	15.2	> 1.7

1. van Kerkwijk et al. 2011 2. Pallanca et al. 2012 3. Romani et ... ton et al. 2013 5. Kaplan et al. 2013
6. McConnell et al 2012 7. Bellm et al 2013 8. Stappers et al 2001

(from Roberts 2013)

Irradiated disc instability



Because of the radiation coming from the central object, there is a transparent → opaque transition in the disc. The vertical structure at a fixed radius a is given by (Lasota 2001)

$$\frac{dP}{dz} = -\rho g_z = -\rho \Omega_K^2 z,$$

$$\frac{d\varsigma}{dz} = 2\rho,$$

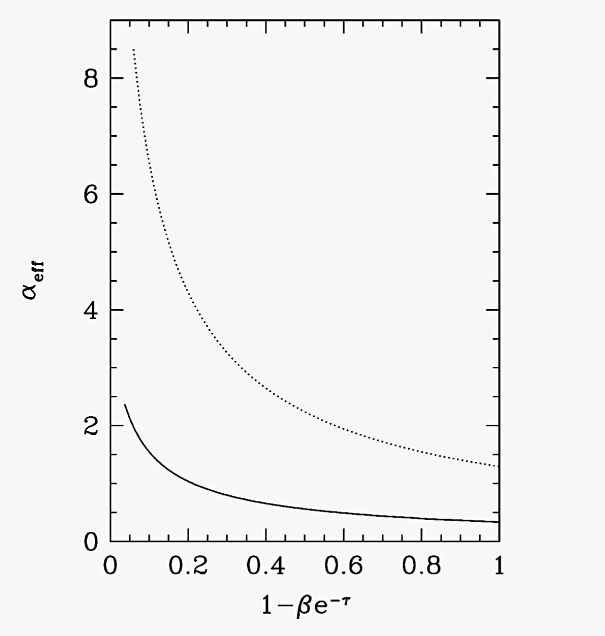
$$\frac{d \ln T}{dz} = \nabla \frac{d \ln P}{dz},$$

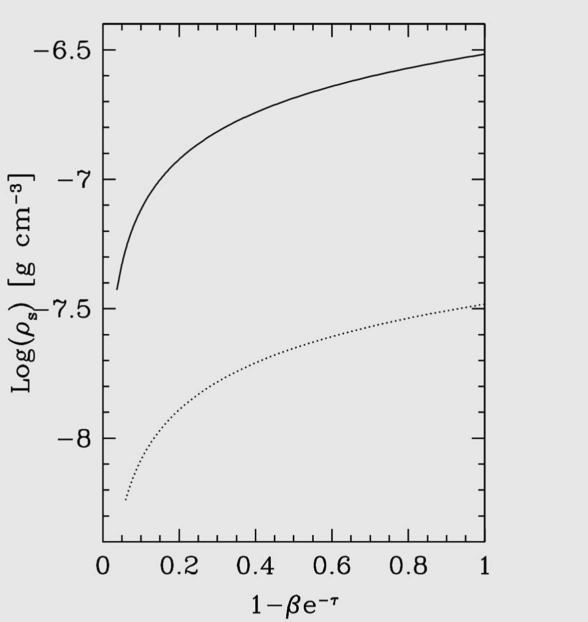
$$\frac{dF_z}{dz} = \frac{3}{2}\alpha \Omega_K P + \frac{dF_t}{dz},$$

Geometrically thin discs, separation of radial and vertical components (Fung & Artymowicz 2014)

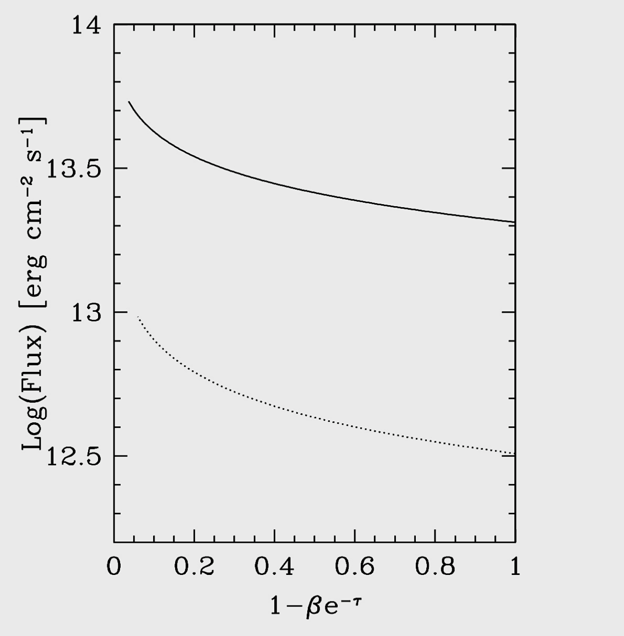
where Ω_k *should be replaced by* $\Omega = \sqrt{\Omega_k^2(1-\beta e^{-\tau})}$ *which contains the effects of the inner irradiation and dilution and* $\beta = \frac{\kappa_{\rm opa} L}{4\pi c G M}$ *is the ratio of the radiation pressure to gravity*

The results show that the disc is being swept by inner radiation, but only a full calculation including radial structure could confirm a ~ yr timescale (in progress...)



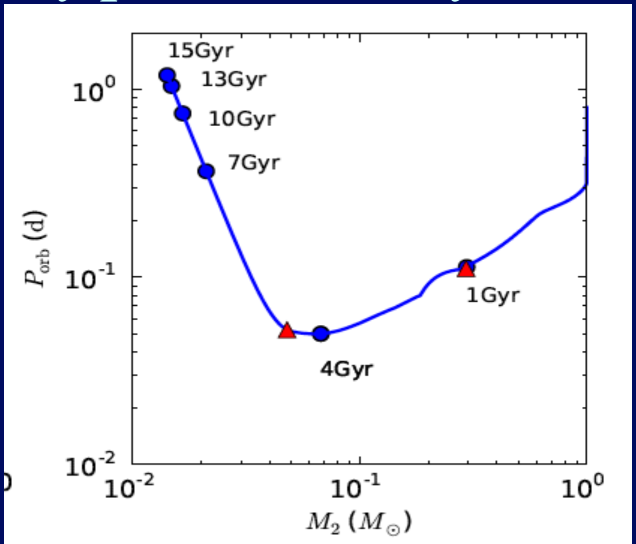


transparent ***opaque***



Conclusions

- *Our evolution tracks show that some "redbacks" are progenitors of "black widows", the evolutionary times are very long (~ few Gyr). New evolutionary path driven by non-standard physics. No common envelope*



(Cheng, Cheng, Tauris & Han 2013)

- *Because of these long accretion phase, it is expected that NS at the "black widow" stage are very massive. No way to put the systems into the "black widow" region with a small efficiency* β *(M > 2 Mo ??? i.e.* **$M_{original} = 2.4 \pm 0.12\ M_\odot$** *van Kwerkwijk, Breton & Kulkarni 2011, Romani et al. 2012, 2015)*

- *Redbacks are sometimes detached and sometimes accreting. The companion is irradiated and settles in a quasi-RLOF state. The disc is blown up and rebuilds on a ~ few years timescale (TBC) Caveat : the description of the disc structure has MANY uncertainties, starting with the very equations...*

- *The redback state, including the quasi-RLOF and the existence/ disapperance of the disc is "all about irradiation..."*

This work is based on

O.G.Benvenuto, M.A. De Vito and J.E. Horvath, ApJ 786, L7 (2014)
O.G.Benvenuto, M.A. De Vito and J.E. Horvath, ApJ 798, 44 (2015)

THANK YOU !