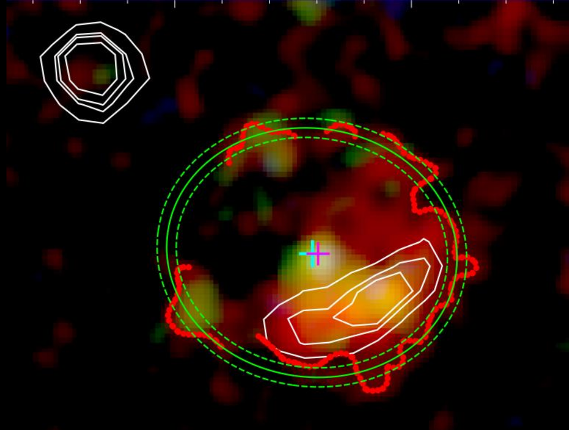
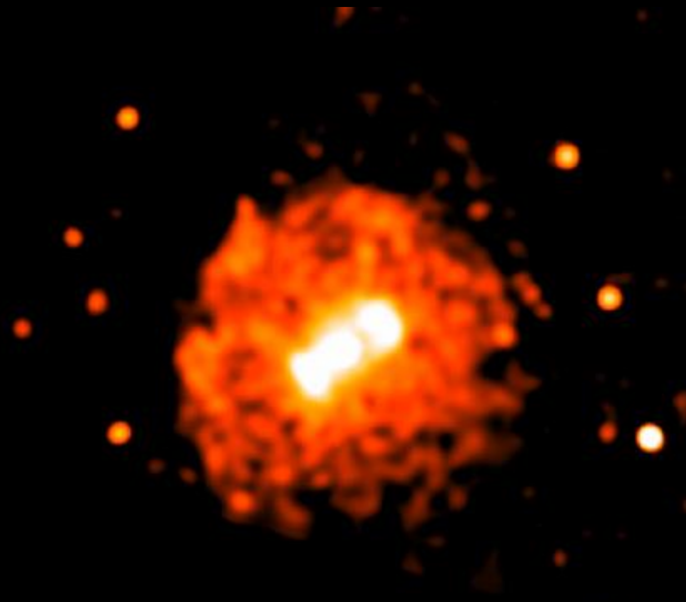
R. C. Smith et al. (1999)



Maitra et al. 2019

How can a neutron star avoid the Ejector stage?

Alena Khokhriakova, Sergei Popov
(SAI MSU)



Heinz et al. 2013

Known HMXBs in SNRs

Recently, several accreting NSs in X-ray binary systems located in supernova remnants (SNRs) have been discovered.

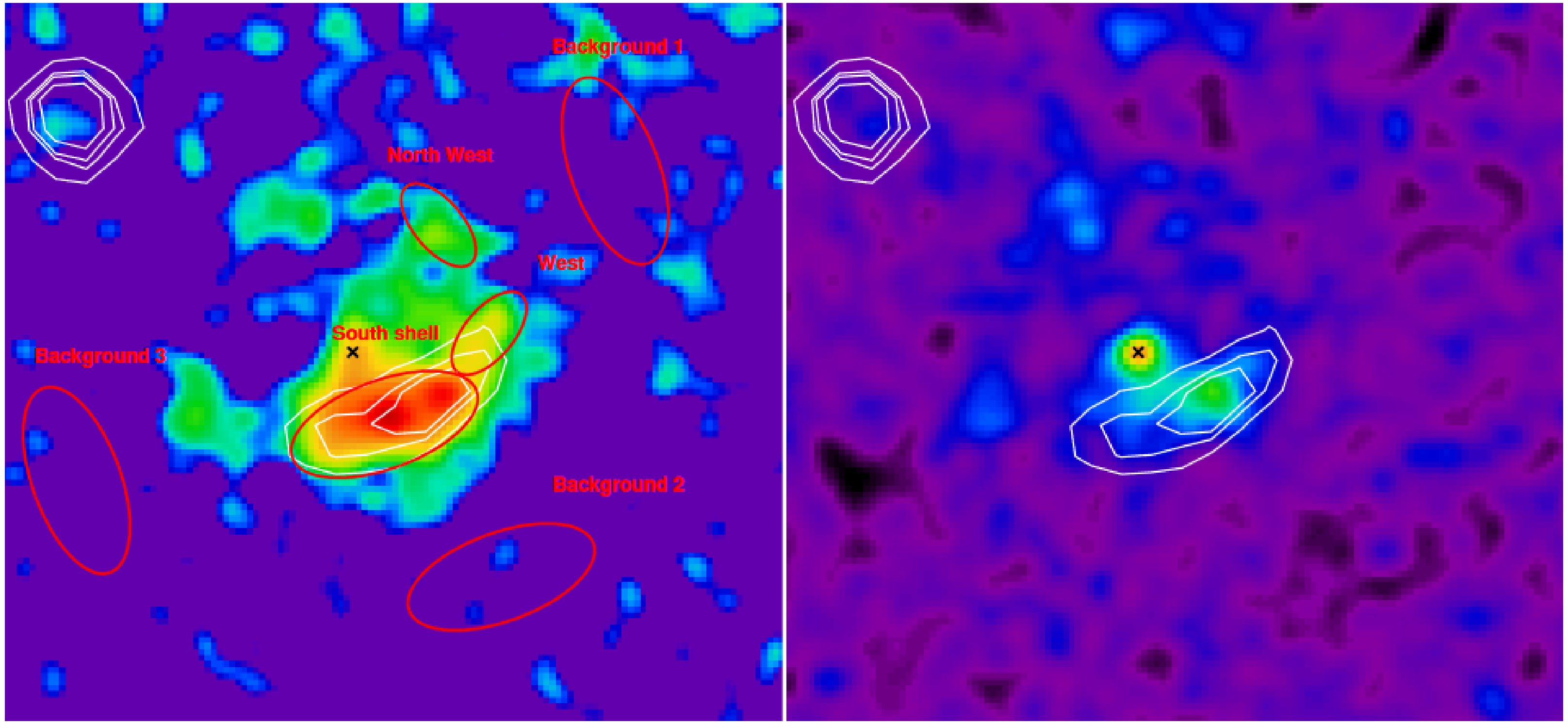
Name	period, s	luminosity erg s^{-1}	age, yrs
SXP 1062	1062	6.9×10^{35}	$(2-4) \times 10^4$
SXP 1323	1323	10^{35} – few $\times 10^{36}$	$\sim 4 \times 10^4$
DEM L241	—	2×10^{35}	-
LXP 4.4	4.4	7×10^{33}	$< 6 \times 10^3$
Circinus X-1	—	$\sim 10^{35*}$	$< 4.6 \times 10^3$
XMMU J050722.1-684758	570	9×10^{34}	$(43-63) \times 10^3$

*Circinus X-1 has a highly variable X-ray luminosity that can reach > 10^{38} erg s^{-1} and the source can be an LMXB

LXP 4.4 (Maitra et al. 2019)

- MCSNR J0513-6724
- supergiant X-ray binary (SGXB)
- spin period 4.4 sec
- luminosity 7×10^{33} erg s^{-1}
- age < 6×10^{3} years
- Companion B2.5Ib
- Orbital period 2.2 days
- Magnetic field from the condition

  $p=p_A$ => $B\sim3\times10^{11}$ G

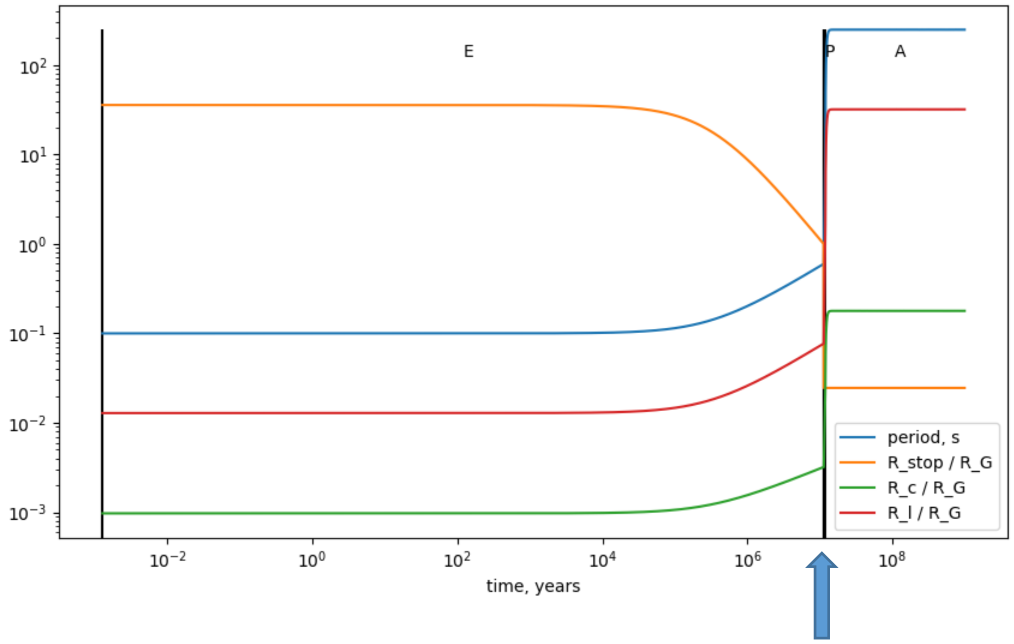


arXiv: 1910.02792

Magneto-rotational evolution

- In recent years, accreting NSs in X-ray binary systems located in SNRs have been discovered
- The standard evolution is Ejector → Propeller → Accretor
- Duration the Ejector stage can be quite long:

$$t_{\mathrm{E}} = \frac{I c^3}{8\pi^2 k_{\mathrm{t}} \mu^2}(p_{\mathrm{E}}^2 - p_0^2) \approx 1.1 \times 10^7 \ \mathrm{yr} \left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{-2}$$



- SNRs have a typical lifetime $\leq 10^5$ years

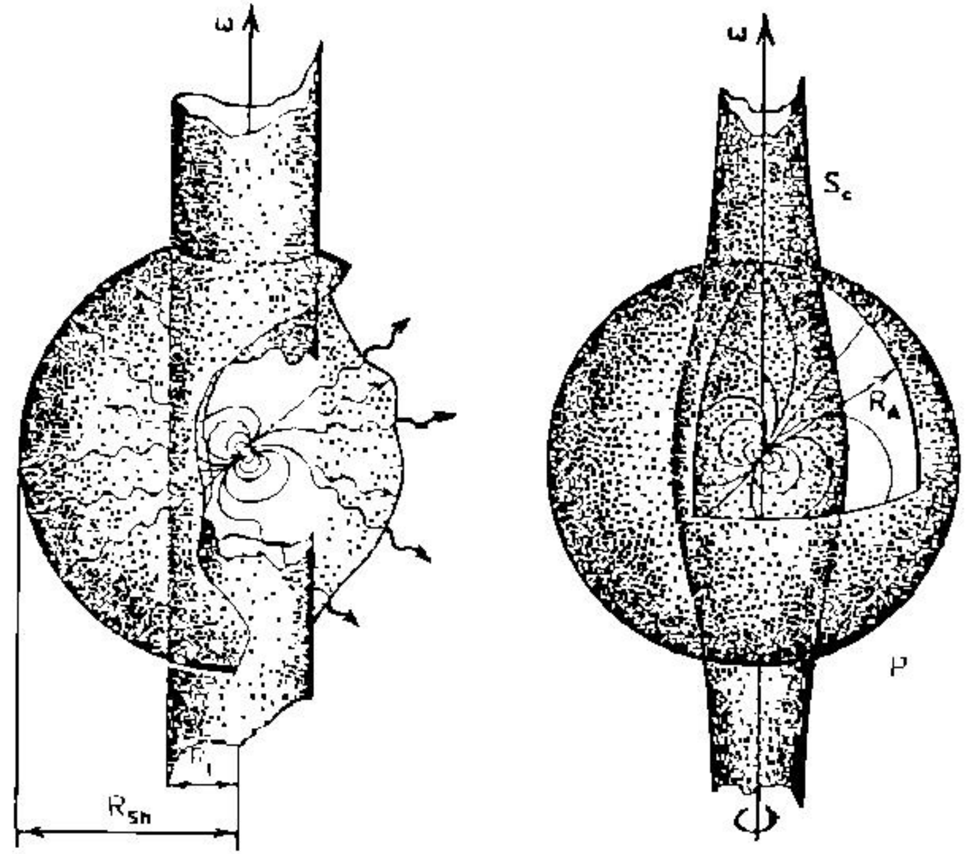
Possible explanations:

1) large initial spin period
2) large initial magnetic field (in some cases)

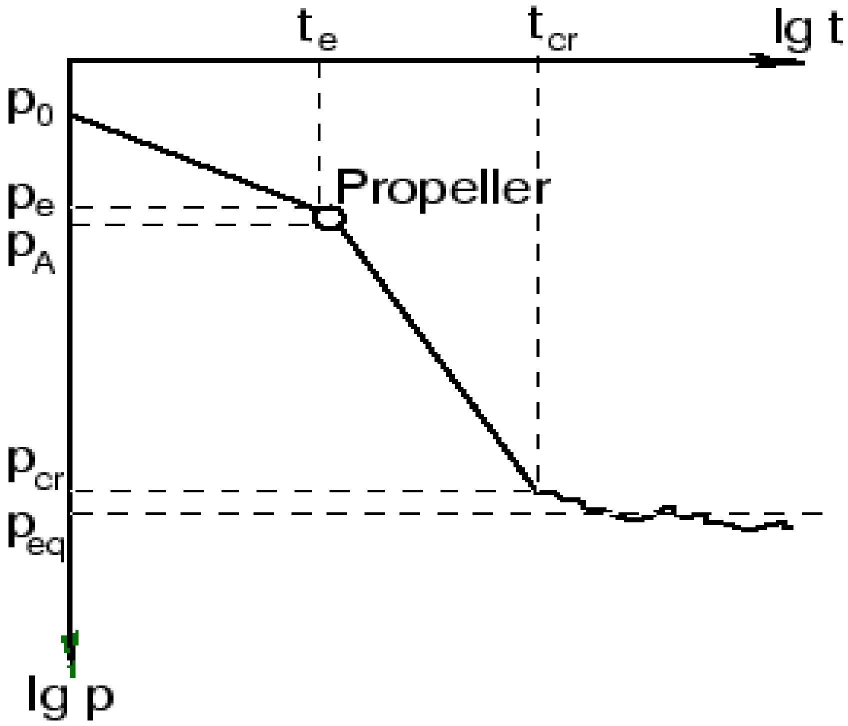
We consider here another idea involving initial fallback stage leading to absence of the Ejector phase.

Critical radii of the model

- The magnetospheric radius: $$R_m = 0.5R_A = \begin{cases} 0.5\left(\frac{2\mu^2 G^2 M_x^2}{\dot{M} v^5}\right)^{1/6}, & \text{if } R_A > R_G; \\ 0.5\left(\frac{\mu^2}{2\dot{M}\sqrt{2GM_x}}\right)^{2/7}, & \text{if } R_A < R_G. \end{cases}$$
- Shvartsman radius: $$R_{Sh} = \left(\frac{8k_t \mu^2 (GM_x)^2 \omega^4}{\dot{M} v^5 c^4}\right)^{1/2}$$
- Gravitational capture radius: $$R_G = \frac{2GM_x}{v^2}$$
- Light cylinder radius: $$R_l = \frac{cp}{2\pi}$$
- Corotation radius: $$R_c = \left(\frac{GM_x p^2}{4\pi^2}\right)^{1/3}$$



Spin evolution



- In the standard scenario the NS is born as Ejector.
  The loss of rotational moment is described
  by the standard magneto-dipole formula:

$$\frac{1}{2}\frac{dI\omega^2}{dt} = -\frac{2}{3}\frac{\mu^2\omega^4}{c^3}\sin^2\chi$$

- After that, the star can proceed to Propeller (if $R_G > R_m > R_c$) or Georotator (if $R_m > R_G$) stage. At propeller phase spindown is very uncertain. We assume the following approach (Shakura 1975):

$$\frac{dp}{dt} = \frac{p^2}{2\pi I}K_{\rm sd}^{(\rm P)}, \qquad K_{\rm sd}^{(\rm P)} = \dot{M}\frac{2\pi}{p}R_{\rm m}^2.$$

- If R_m becomes less than R_c, accretion stage begins, where both — spin-up and spin-down — momenta co-exist:

$$\frac{dp}{dt} = \frac{p^2}{2\pi I}(K_{\rm sd}^{\rm A} - K_{\rm su}^{\rm A}) \qquad K_{\rm sd}^{(\rm A)} = \frac{k_t\mu^2}{R_c^3} \qquad K_{\rm su}^{(\rm A)} = \dot{M}\eta_t\Omega R_{\rm G}^2.$$

Hysteresis

Transitions are determined by pressure balance at critical radii.

However, this equality can be reach at different radii for direct and backwards.

So, there is an asymmetry in Ejector ↔ Propeller transition, first noticed by Shvartsman (1971):

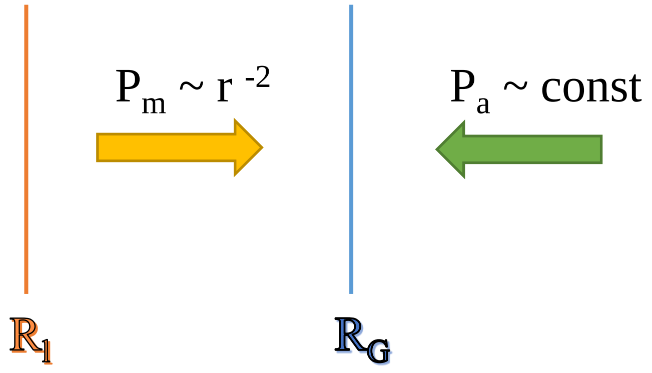
$$p_{\mathrm{E}\to\mathrm{P}} = \frac{2\pi}{c}\left(\frac{2k_t\mu^2}{3v\dot{M}}\right)^{1/4} =$$

$$= 0.6\left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{1/2}\left(\frac{\dot{M}}{10^{14}\ \mathrm{g\ s^{-1}}}\right)^{-1/4}\left(\frac{v}{10^{8}\ \mathrm{cm\ s^{-1}}}\right)^{-1/4}\ \mathrm{s};$$

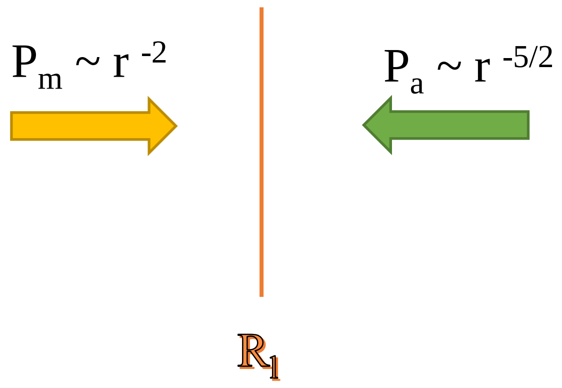
$$p_{\mathrm{P}\to\mathrm{E}} = \frac{2\pi}{c}\left(\frac{\mu^4}{8GM_{\mathrm{x}}\dot{M}^2}\right)^{1/7} =$$

$$= 0.19\left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{4/7}\left(\frac{\dot{M}}{10^{14}\ \mathrm{g\ s^{-1}}}\right)^{-2/7}\ \mathrm{s}.$$

Direct transition
Ejector→Propeller



Reverse transition
Propeller→Ejector



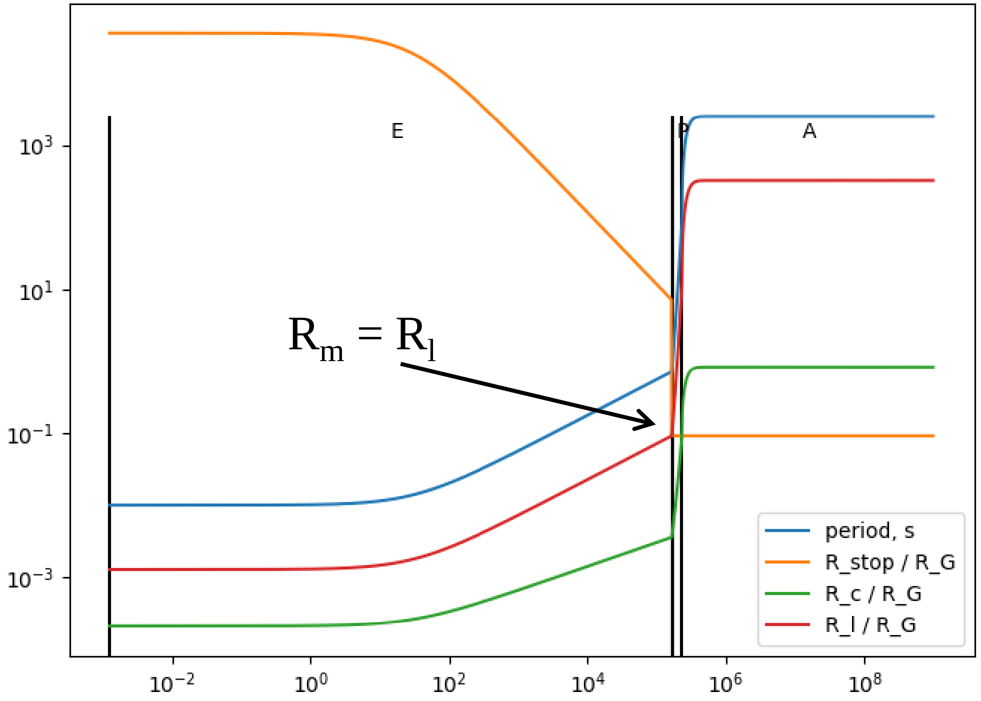
Comments on the work of Ho et al. 2020

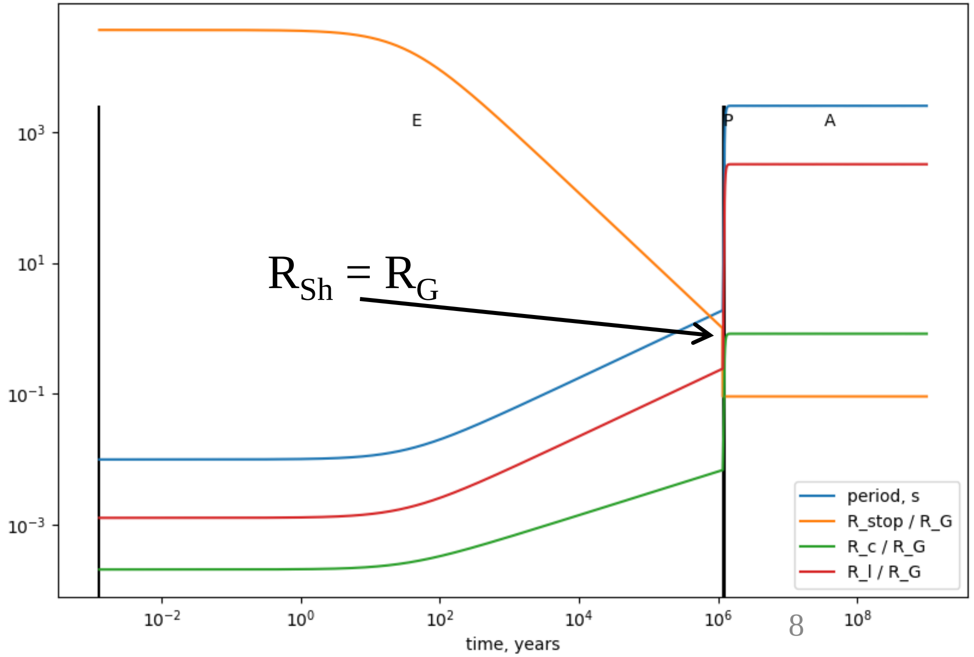
In Ho et al. (2020) the condition of the E-P transition is $R_m = R_l$, i.e.

$$P < 2\pi r_{\rm m}/c = 150\ {\rm ms}\ B_{13}^{4/7}\dot{M}_{-10}^{-2/7}$$

The correct condition is $R_{Sh} = R_G$.

Given this, **the Ejector stage becomes much longer**, and therefore the explanation of such systems becomes even more problematic.





Fallback accretion

After formation of an NS, some amount of the progenitor star material expelled in the supernova explosion can fall back onto the compact object.

At late times, fallback accretion rate follows a simple power law: $\dot{M} \sim t^{-5/3}$

Change in magnetic field:

$$B(t) = \frac{B_0}{1 + \frac{\Delta M(t)}{M_c}}$$

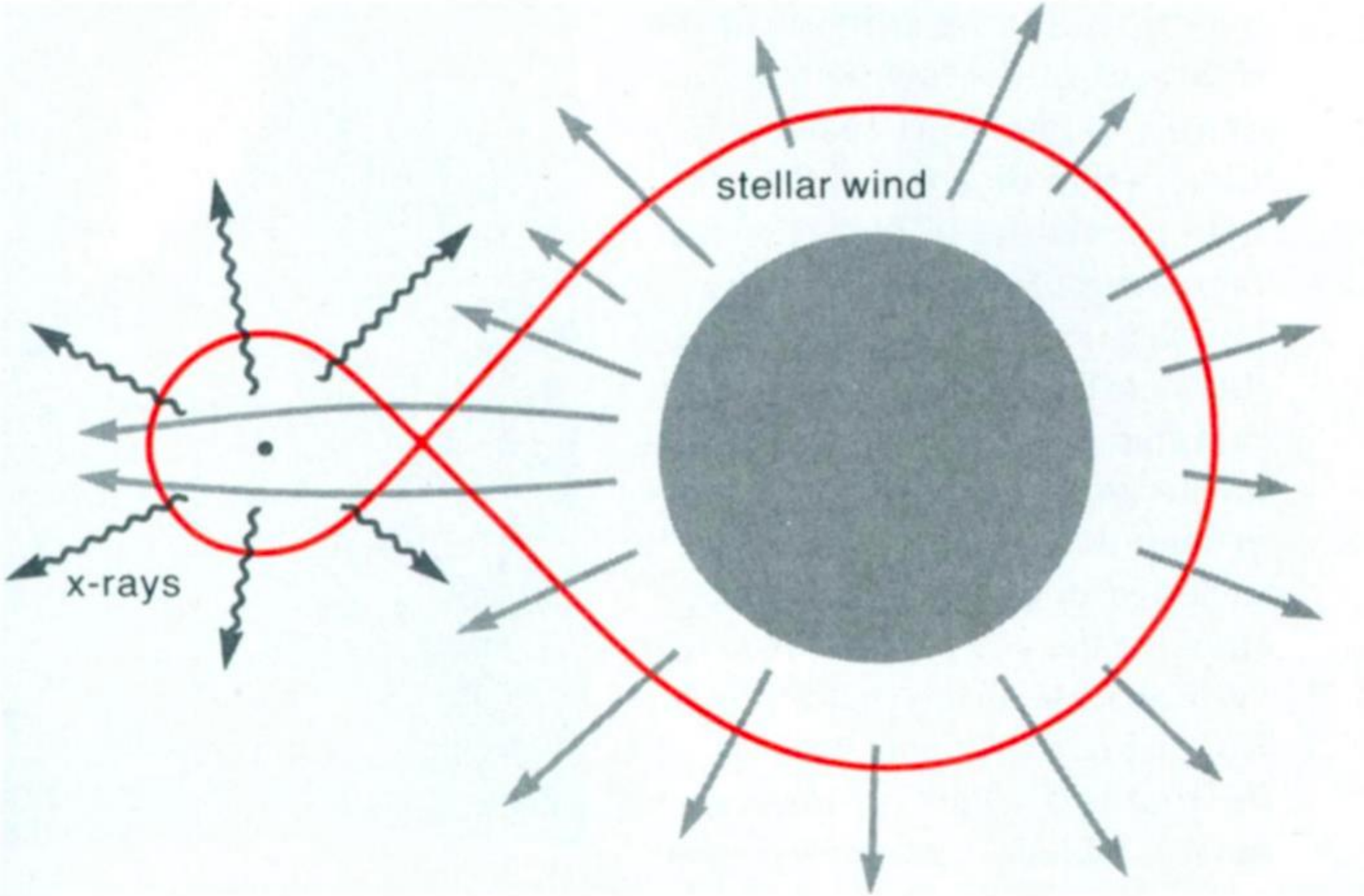
The Roche lobe radius

$$r_L = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

For LXP 4.4:

$r_L \sim 10^{11}$cm

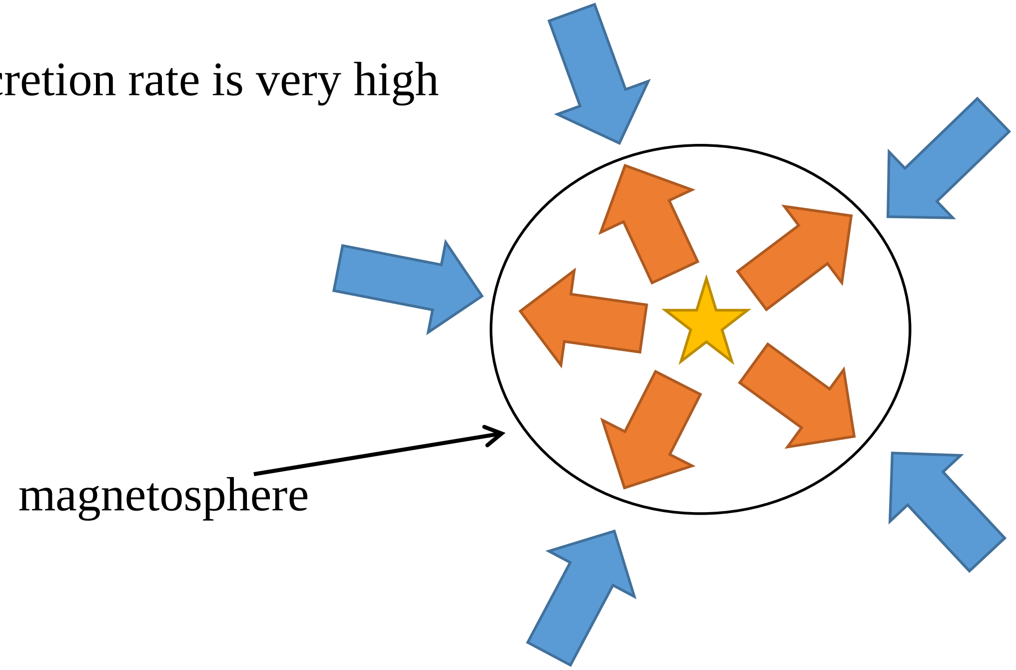
$t_{ff} \sim 8$ hours



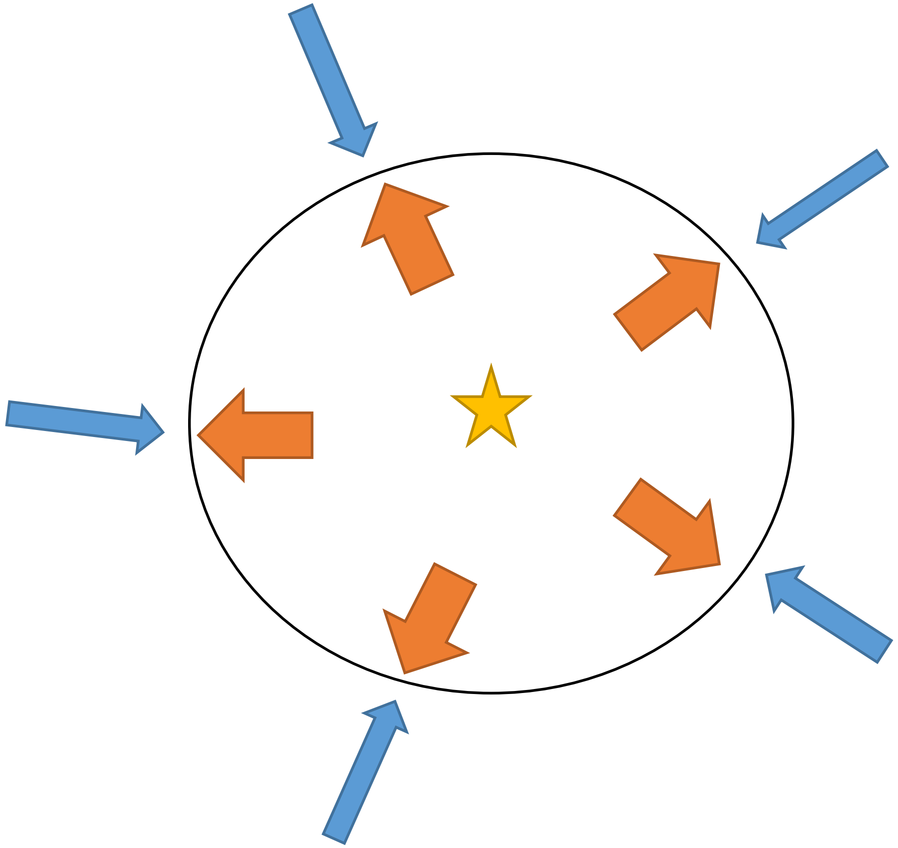
Ronald E. Taam and Bruce A. Fryxell 1989

Magnetosphere evolution and fallback

Fallback. Accretion rate is very high



Wind accretion. Magnetosphere has grown



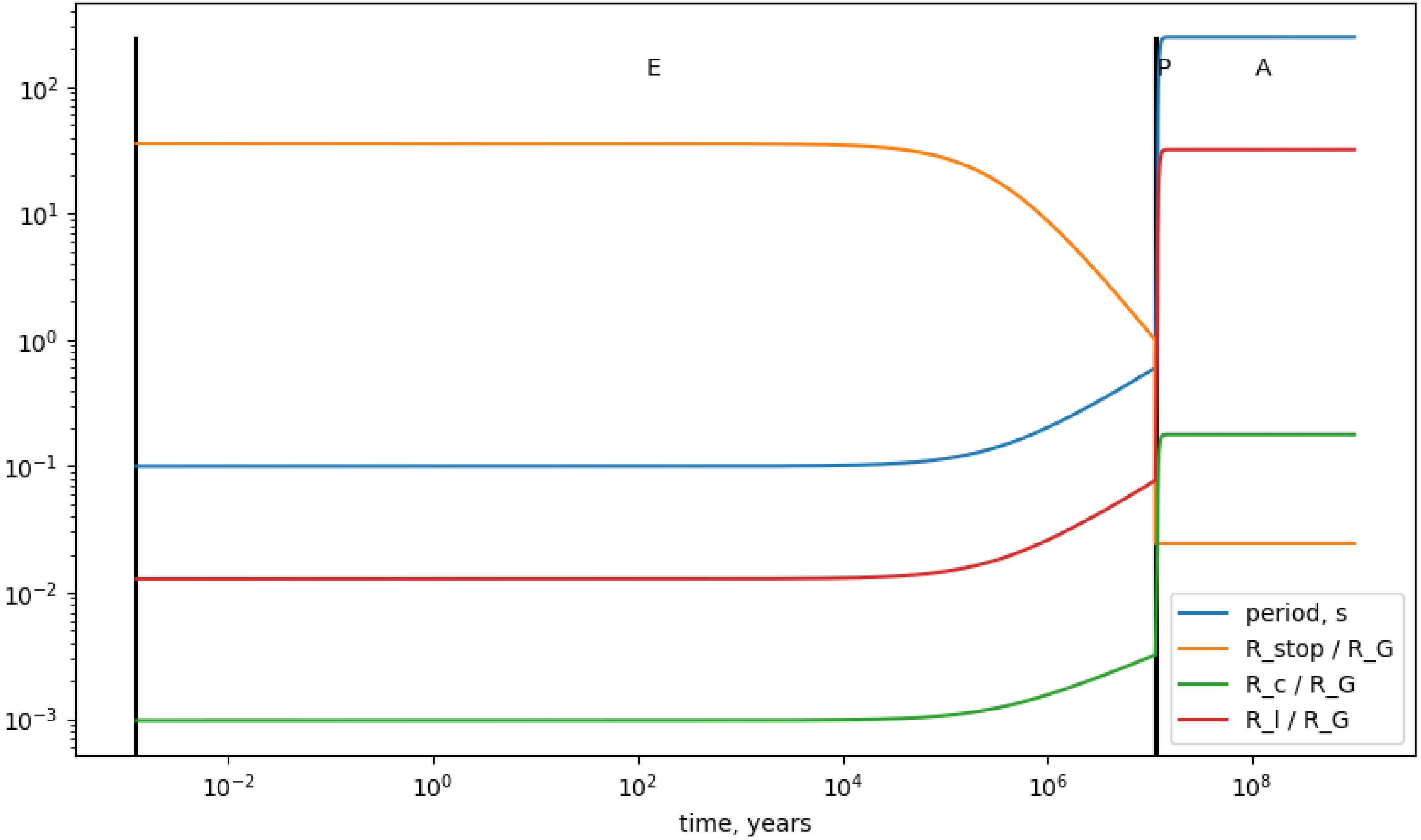
One of the following three situations may occur at the end of fall-back:

1) $R_m < R_c$ Accretor
2) $R_c < R_m < R_l$ Propeller
3) $R_m > R_l$ Ejector

If an NS is not an Ejector at this moment, it will not enter this stage in the future and will start accreting quite fast.

Results. Standard evolution

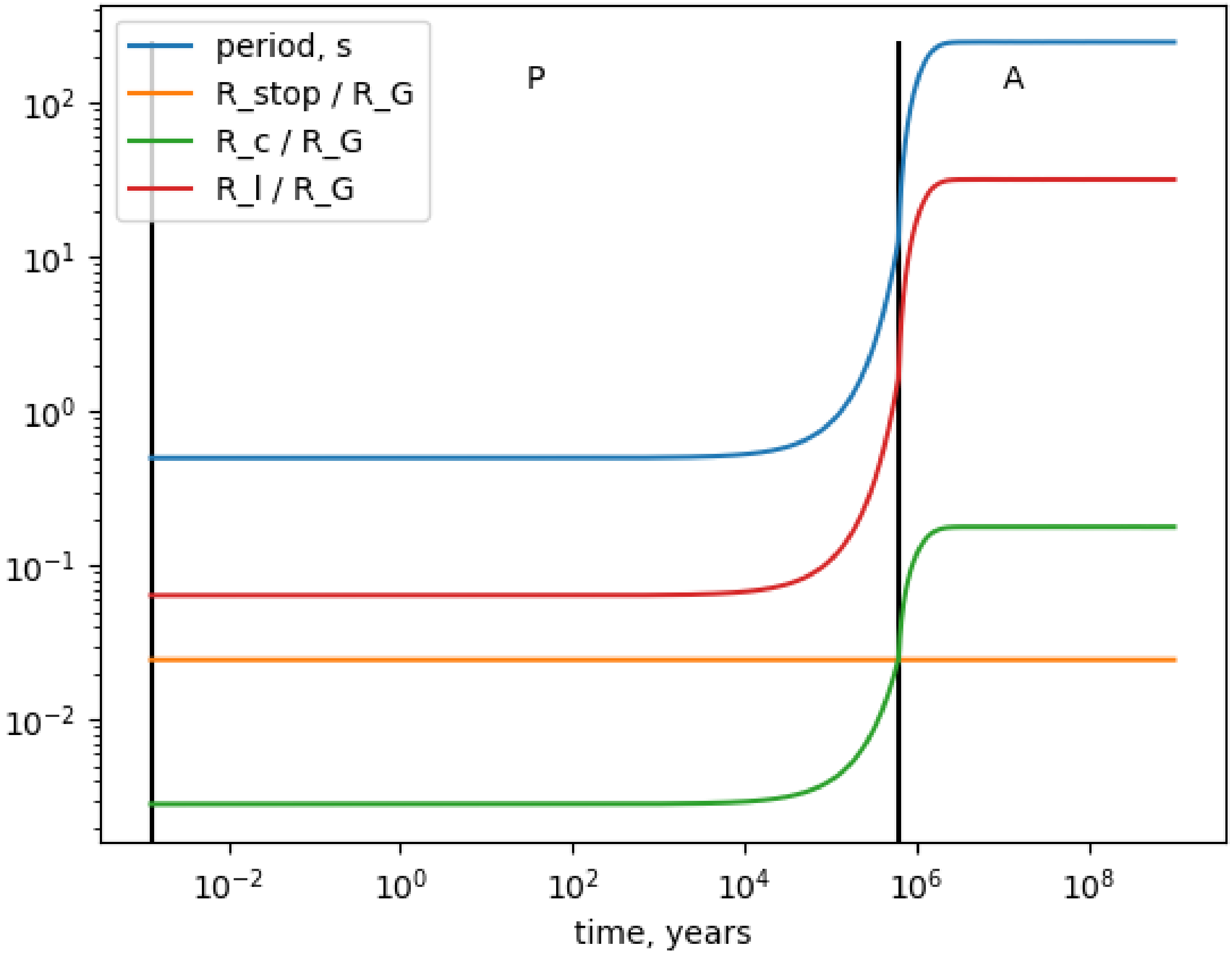
- $B_0 = 10^{12}$ G
- $P_0 = 0.1$ s
- $\dot{M} = 10^{14}$ g/s
- $v_{wind} = 10^8$ cm/s
- Orbital period 2.2 d



Results. The hysteresis effect

- $B_0 = 10^{12}$ G
- $P_0 = 0.5$ s
- $\dot{M} = 10^{14}$ g/s
- $v_{wind} = 10^8$ cm/s
- Orbital period 2.2 d

When fallback is over,
the NS is at Propeller stage.



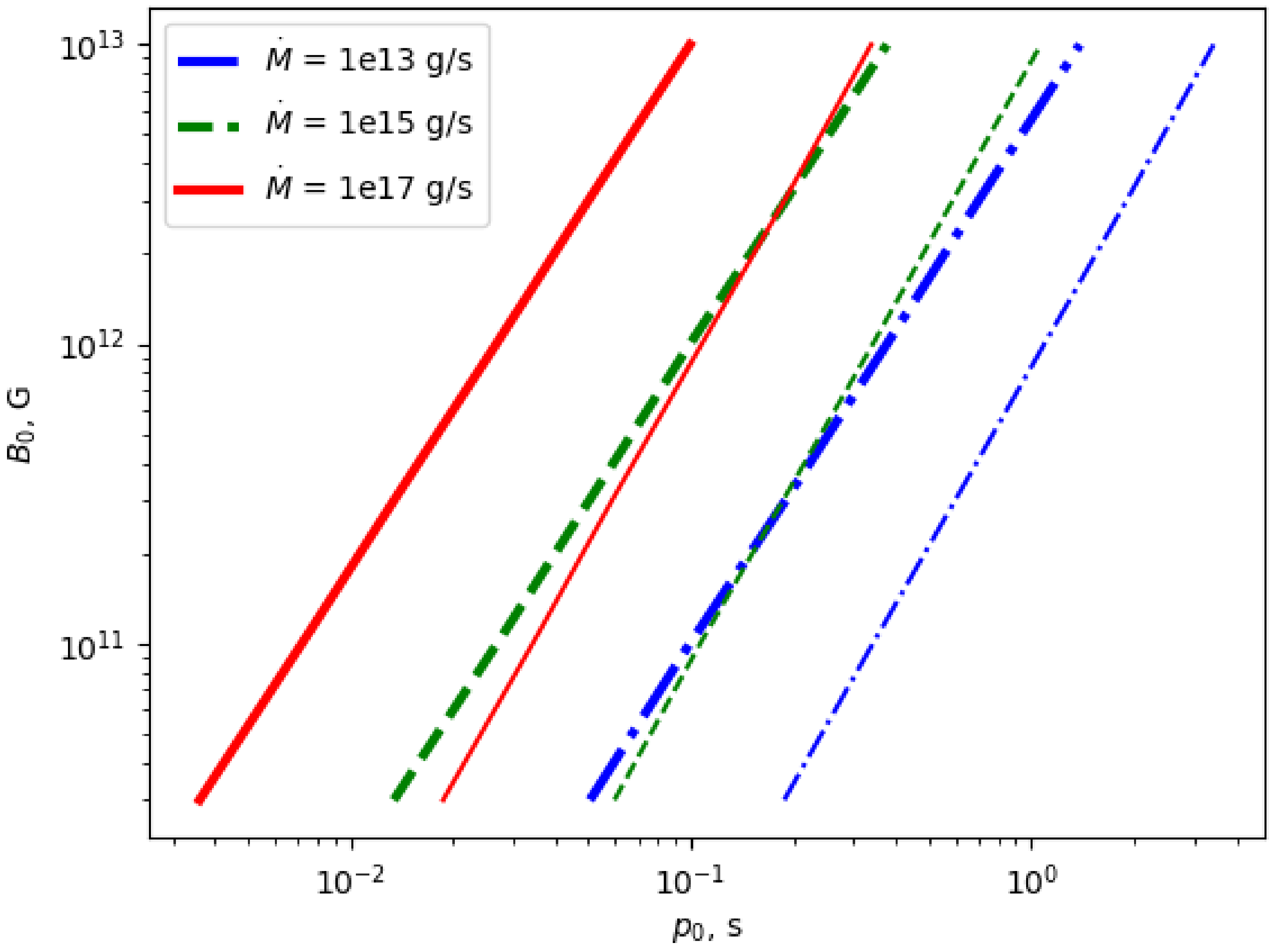
Who can become a young Accretor?

- For different $\dot{M}$ we calculate critical values of B_0 and P_0, for which (if the period is higher or magnetic field is less than critical value) the NS will not enter the Ejector stage.
- Bold and thin lines represent the presence and absence of the hysteresis effect, respectively.
- Equation of the line with hysteresis:

$$B_0 = \left(\left(\frac{cP_0}{\pi} \right)^{7/2} \frac{2\dot{M}\sqrt{2GM_x}}{R_x^6} \right)^{\frac{1}{2}}$$

- Without hysteresis:

$$B_0 = \left(\left(\frac{cP_0}{2\pi} \right)^{4} \frac{v\dot{M}}{2k_t R_x^6} \right)^{\frac{1}{2}}$$



Conclusions

- Presence of a fallback stage can change evolution and observational properties of neutron stars in binary systems;
- The hysteresis effect allows a young neutron star in a HMXB to avoid the Ejector stage;
- Such neutron stars can start accreting at young ages;
- Some of the HMXB in SNRs can be exmaples of such systems.

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