On the Nature of Long-Period X-ray Pulsars

Nazar R. Ikhsanov
Pulkovo Observatory, St. Petersburg, Russia
(Marie Curie Fellow)

* * *

- **Long-period X-ray Pulsars (LPXPs)**

- **Evolutionary tracks of massive X-ray binaries**

- Conclusions

MARIE CURIE
FELLOWSHIP
ASSOCIATION

High Mass X-ray Binaries

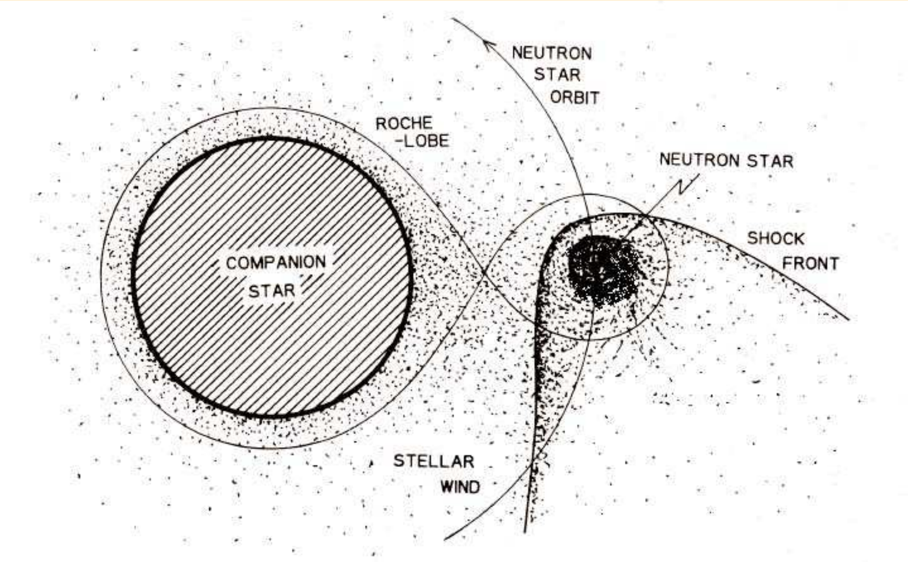
★ Wind-fed Accretion

$$R_{\rm opt} < R_{\rm Roche}$$

$$\dot{\mathfrak{M}}_{\rm c} = \pi \, r_\alpha^2 \, \rho_\infty \, V_{\rm rel}$$

$$r_\alpha = \frac{2GM_{\rm ns}}{V_{\rm rel}^2}$$

$$|\vec{V}_{\rm rel}|^2 = |\vec{V}_{\rm ns} + \vec{V}_{\rm w}|^2 + V_{\rm s}^2$$

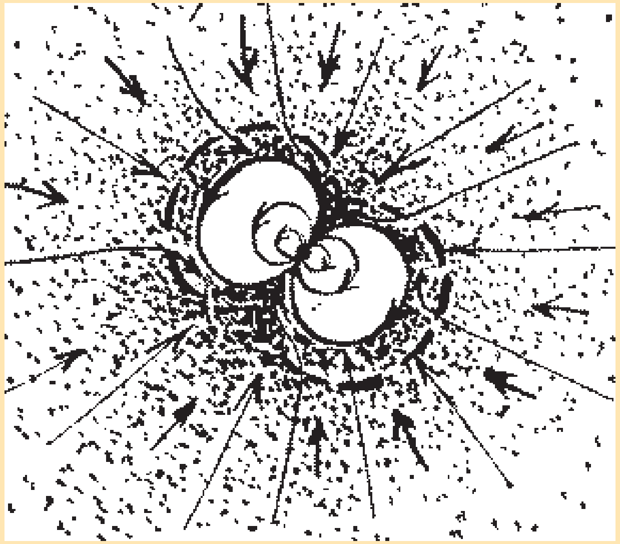


★ Accretion-powered pulsar

$$\dot{\mathfrak{M}}_{\rm a} = \frac{L_{\rm X} R_{\rm ns}}{GM_{\rm ns}}$$

$$B(R_{\rm ns}) \sim 10^{12}\,{\rm G}$$

(Cyclotron line in X-ray spectrum)

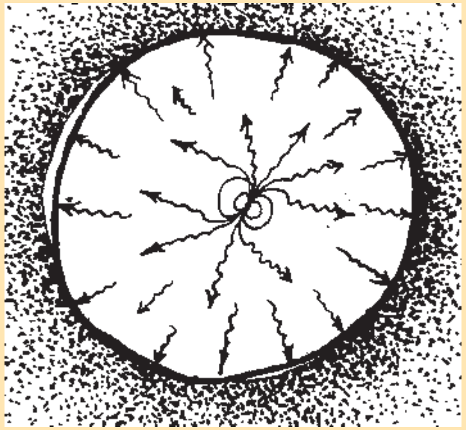


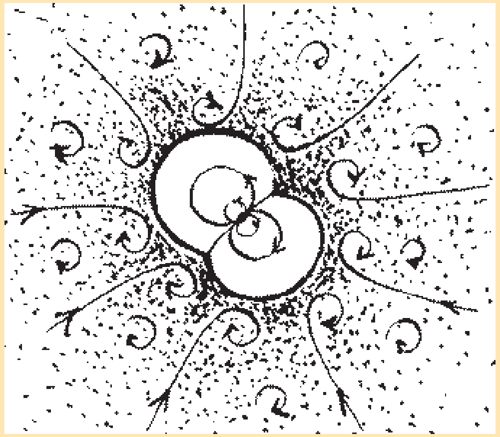
Long-period X-ray pulsars

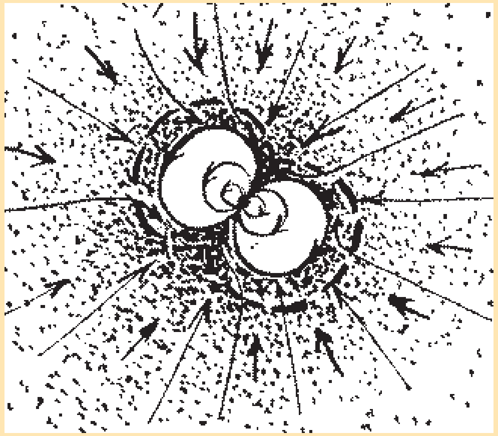
Name	Sp. type	P_s, s	P_orb, d	$\log L_\mathrm{x}$
J170006-4157	–	715	–	34.7
0352+309 (X Per)	B0 Ve (O9.5 IIIe)	837	250	34.7 – 35.5
J1037.5-5647	B0 V-IIIe	862	–	34-35
J2239.3+6116	B0 Ve	1247	262.2	33 – 36
J0103.6-7201	O5 Ve	1323	–	35.3 – 36.8
J0146.9+6121 (V831 Cas)	B1 III-Ve	1412	–	34.6 – 36
2S 0114+650	B1 Ia	10008	11.6	34.7 – 35

Canonical Evolutionary Track

Ejector ⟶ **Propeller** ⟶ **Accretor**







Assumption: Transition to Accretor occurs at $R_{\mathrm{m}} = R_{\mathrm{cor}}$

$$P_{\max} \lesssim \underline{15\ \mathrm{s}} \times m^{-2/7} R_6^{-3/7} L_{35}^{-3/7} B_{12}^{6/7}$$

$$L_{\mathrm{x}} < \underline{10^{31}\ \mathrm{erg/s}} \times m^{-2/3} P_{700}^{-7/3} B_{12}^{2}$$

Something is incorrect...

2S 0114+650 / LSI +65010

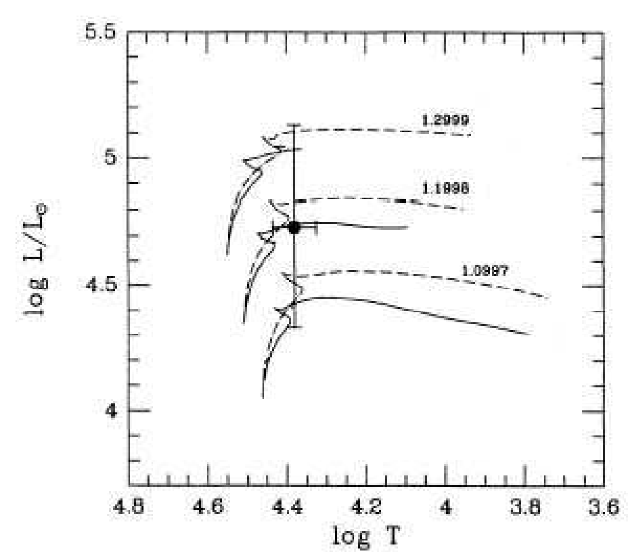
Neutron star

$$P_{\rm s} \simeq 10008\,{\rm s}$$

$$\dot{P} \simeq -10^{-7}\ {\rm s/s}$$

$$\frac{P_{\rm s}}{\dot{P}} \simeq 3000\ {\rm yr}$$

Evolutionary track



Normal companion

Observed: B1 Ia

Progenitor: O9.5 V

$$\frac{\dot{M}_{\rm loss}({\rm B1\ Ia})}{\dot{M}_{\rm loss}({\rm O9.5\ V})} \sim 10$$

★ Assumption about the spin-down of the NS in the accretor state **is not effective**

★ Magnetar: $B_0 \sim 10^{15}\,{\rm G} \longrightarrow B(t = 10^5\,{\rm yr}) \sim 10^{14}\,{\rm G}$. Putting $P_{\rm max} = P_{\rm cd}(R_{\rm m} = R_{\rm cor})$, one finds:

$$\dot{\mathfrak{M}}_{\rm c}(t_{\rm sd}) \lesssim 2\times 10^{13}\,{\rm g/s} \times m^{-5/3}\,{\mu_{32}}^2 \left(\frac{P_{\rm cd}}{10^4\,{\rm s}}\right)^{-7/3} \Longrightarrow \frac{\dot{\mathfrak{M}}_{\rm a}}{\dot{\mathfrak{M}}_{\rm c}(t_{\rm sd})} \simeq 250$$

Accretion flow geometry

★ **Evolution of the spin period of accretion-powered pulsars:**

$$2\pi\ I\ \frac{d}{dt}\left(\frac{1}{P_{\rm s}}\right) = K_{\rm su} + K_{\rm sd}$$

$$K_{\rm sd} = -\,k_{\rm t}\ \left(\mu^2 / R_{\rm c}^3\right)$$

$$K_{\rm su} = \begin{cases} \dot{\mathfrak{M}}_{\rm a}\ \sqrt{GM_{\rm ns}R_{\rm m}}, & \text{disk accretion,} \\ \frac{1}{4}\ \xi\ \dot{\mathfrak{M}}_{\rm a}\ \Omega_{\rm orb}\ r_{\alpha}^2, & \text{spherical accretion.} \end{cases}$$

★ **Equilibrium period:**

$$P_{\rm eq} = \begin{cases} 10\ {\rm s}\ \times\ m^{-5/7}\ \mu_{30}^{6/7}\ \dot{\mathfrak{M}}_{15}^{-3/7}, & \text{disk accretion,} \\ 900\ {\rm s}\ \times\ m^{-3/2}\ \mu_{30}\ \dot{\mathfrak{M}}_{15}^{-1/2}\ V_{500}^2\ P_{250}^{1/2}\ \xi_{0.2}^{-1/2}, & \text{spherical accretion} \end{cases}$$

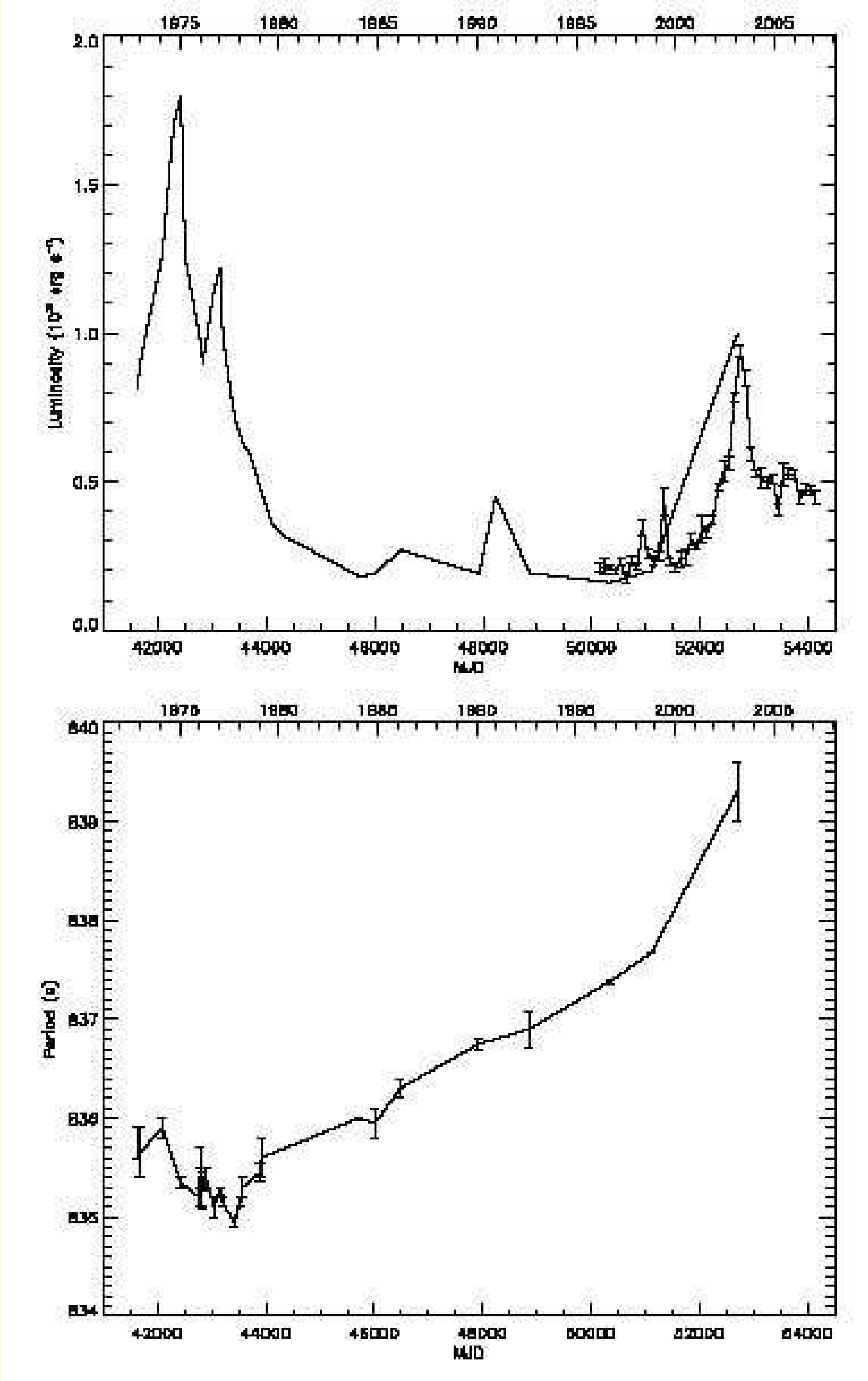
★ **For the disk accretion case:**

$$P_{\rm eq} \ll P_{\rm s} \Longrightarrow \begin{cases} \dot{P}\ \simeq\ P_{\rm s}^2\ \dfrac{\dot{\mathfrak{M}}_{\rm a}\sqrt{GM_{\rm ns}r_{\rm m}}}{2\pi I}\ \sim\ -5\times10^{-8}\,{\rm s/s}, \\ \Delta t\ \simeq\ \dfrac{2\pi I}{\dot{\mathfrak{M}}_{\rm a}\sqrt{GM_{\rm ns}r_{\rm m}}}\left(\dfrac{1}{P_{\rm s}} - \dfrac{1}{P_0}\right)\ \lesssim\ 100 - 1000\ {\rm yr} \end{cases}$$

I. Regular spin-up at a high rate

II. Very short life-time of LPXPs

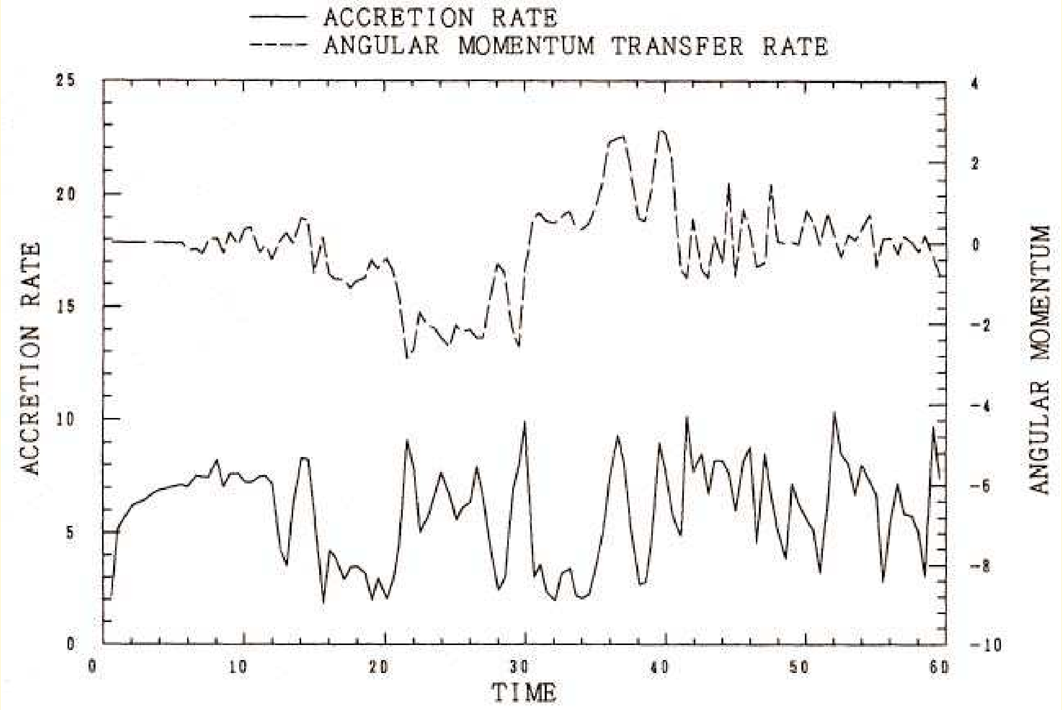
X Persei



$V_{\mathrm{rel}} \simeq 350 - 400$ км/с $\qquad \mu \simeq 1.7 \times 10^{30}$ Гс · см^3

$$P_{\mathrm{eq}} = 900 \text{ s} \times m^{-3/2}\, \mu_{30}\, \dot{\mathfrak{M}}_{15}^{-1/2}\, V_{500}^{2}\, P_{250}^{1/2}\, \xi_{0.2}^{-1/2}$$

Spherical (Bondi) accretion !

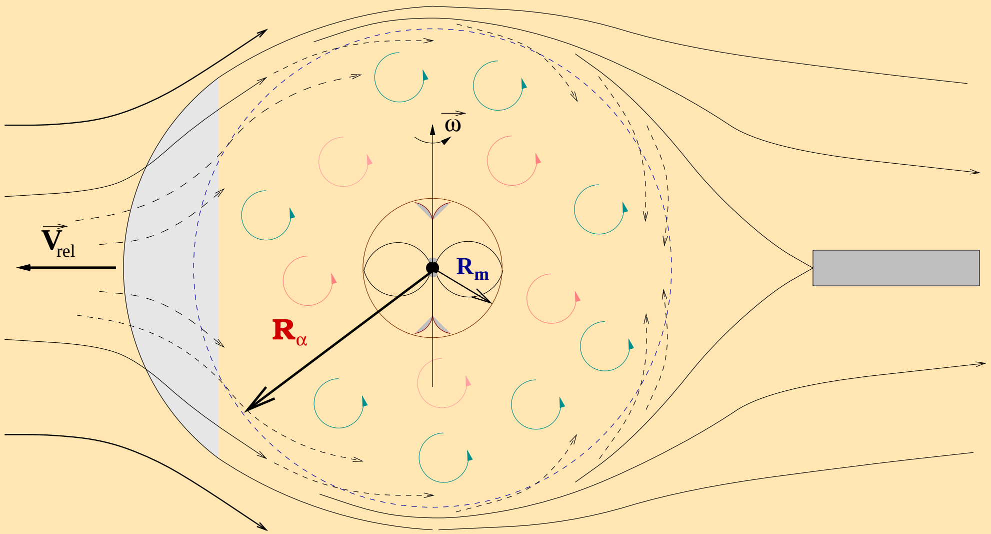


Supersonic propeller $r_{\mathrm{m}} > r_{\mathrm{c}}$ (Spherical accretion flow geometry)

$$R_{\mathrm{m}} \simeq \underline{1.4\times10^{9}\,\mathrm{cm}} \times \mu_{30}^{4/7}\,\dot{\mathfrak{M}}_{14.3}^{-2/7}\,M_{1.4}^{-1/7}$$

$$T_{\mathrm{ff}}(R_{\mathrm{m}}) \simeq \underline{4\times10^{8}\,\mathrm{K}} \times M_{1.4}\left(\frac{r_{\mathrm{m}}}{1.4\times10^{9}\,\mathrm{cm}}\right)^{-1}$$

$$N(R_{\mathrm{m}}) \simeq \underline{4.4\times10^{10}\,\mathrm{cm}^{-3}} \times \mu_{30}^{2}\,T_{8.6}^{-1}\left(\frac{r_{\mathrm{m}}}{1.4\times10^{9}\,\mathrm{cm}}\right)^{-6}$$



Heating time: $t_{\mathrm{ff}}(R_{\mathrm{m}}) \simeq \underline{3\ \mathrm{s}} \times M_{1.4}^{-1/2}\left(\frac{R_{\mathrm{m}}}{1.4\times10^{9}\,\mathrm{cm}}\right)^{3/2}$

Cooling time: $t_{\mathrm{br}}(R_{\mathrm{m}}) \sim \underline{10^{5}\ \mathrm{s}} \times T_{8.6}^{1/2}\left(\frac{N(R_{\mathrm{m}})}{4.4\times10^{10}\ \mathrm{cm}^{-3}}\right)^{-1}$

The hot envelope forms if

$$\boxed{\dot{\mathfrak{M}}_{0} \lesssim 3.5\times10^{17}\ \mathrm{g/s}\ \times m\,V_{8}}$$

Correction of the DFP-scenario by a factor of 175 !

Метод: Davies, R.E. & Pringle, J.E., 1981, MNRAS 196, 209
Коррекция: Ikhsanov, N.R. 2002, A&A, 381, L61

Сверхзвуковой пропеллер: Условие образования оболочки

$$\Gamma = \frac{[\text{Темп нагрева конвективных элементов}]}{[\text{Радиационные потери конвективных элементов}]}$$

Условие охлаждения турбулентной оболочки:

$$\Gamma(r) = M_{\rm Mach}^2 \left[\frac{V_{\rm t}\, t_{\rm br}}{r}\right] = \frac{V_{\rm t}^3\, t_{\rm br}}{V_{\rm s}^2\, r} < 1, \qquad \Gamma \propto r^{-3/2} \tag{1}$$

$t_{\rm br}$ время охлаждения вследствии тормозного излучения:

$$t_{\rm br} = 6.3 \times 10^4 \left[\frac{T}{10^9\ \text{K}}\right]^{1/2} \left[\frac{n}{10^{11}\ \text{см}^{-3}}\right]^{-1} \text{с} \tag{2}$$

n – плотность плазмы оболочки:

$$n(r_\alpha) \simeq \frac{\dot{M}_{\rm c}}{\pi r_\alpha^2 V_\infty m_{\rm p}}. \tag{3}$$

Скорость турбулентных движений в оболочке, вызванных эффектом пропеллера:

$$V_{\rm s} \sim V_{\rm t} \sim V_{\rm ff}(r) = \sqrt{2GM_{\rm ns}/r} \tag{4}$$

Вириальная температура:

$$T(r) \sim T_{\rm ff}(r) = (GM_{\rm ns} m_{\rm p})/(kr) \tag{5}$$

Радиус гравитационного захвата материи нейтронной звездой (радиус Бонди):

$$r_\alpha = (2GM_{\rm ns})/V_\infty^2 \tag{6}$$

* * *

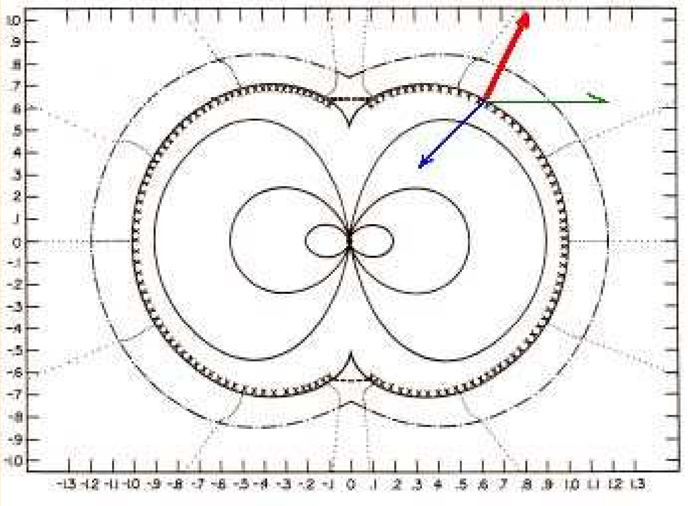
$$\dot{M}_{\rm c} \lesssim \dot{M}_{\rm max} = 3.5 \times 10^{17} \left[\frac{M_{\rm ns}}{M_\odot}\right] \left[\frac{V_\infty}{10^8\ \text{cm s}^{-1}}\right] \text{г/с}$$

Supersonic propeller $\Longrightarrow$ Subsonic propeller $\Longrightarrow$ Accretor

$$a_{\rm curv} = \frac{V_{T_{\rm i}}^2(r_{\rm m})}{R_{\rm curv}(\theta)}$$

$$a_{\rm grav} = \frac{GM_{\rm ns}}{R_{\rm m}^2(\theta)}$$

$$a_{\rm cent} = \Omega_{\rm s}^2 \; r_{\rm m}$$



$$g_{\rm eff} = \frac{GM_{\rm ns}}{R_{\rm m}^2(\theta)} - \frac{V_{\rm T_i}^2(r_{\rm m})}{R_{\rm curv}(\theta)} > 0$$

$$T(r_{\rm m}) \lesssim T_{\rm cr} \simeq (0.1 - 0.3)\, T_{\rm s}(R_{\rm m})$$

Cooling at $R_{\rm m}$ dominates heating if

$$\boxed{P_{\rm s} \gtrsim P_{\rm br}(t_{\rm sd}) \simeq 2000\,{\rm s} \; \times \; m^{-4/21} \; \dot{\mathfrak{M}}_{15}^{-5/7} \left(\frac{B(t_{\rm sd})}{0.3\, B_{\rm cr}}\right)^{16/21} \left(\frac{R_{\rm ns}}{10^6\,{\rm cm}}\right)^3}$$

Correction of DFP-model by a factor of 8 !

$P_{\rm s}(R_{\rm m}{=}R_{\rm cor}) \ll P_{\rm br}$ $\longrightarrow$ New state: Subsonic propeller

Метод: Davies, R.E. & Pringle, J.E., 1981, MNRAS 196, 209
Коррекция: Ikhsanov, N.R. 2001, A&A, 368, L5

Дозвуковой пропеллер: Условие существования оболочки

Условие охлаждения турбулентной оболочки:

$$\Gamma(r) = M_{\rm Mach}^2 \left[\frac{V_{\rm t}\ t_{\rm br}}{r}\right] = \frac{V_{\rm t}^3\ t_{\rm br}}{V_{\rm s}^2\ r} < 1, \qquad \Gamma \propto r^{1/2} \tag{1}$$

$t_{\rm br}$ время охлаждения вследствии тормозного излучения:

$$t_{\rm br} = 6.3 \times 10^4 \left[\frac{T}{10^9\,{\rm K}}\right]^{1/2} \left[\frac{n}{10^{11}\ {\rm см}^{-3}}\right]^{-1} {\rm c} \tag{2}$$

n – плотность плазмы на границе магнитосферы:

$$n(r_{\rm m}) = \frac{\mu^2}{8\pi\ k\ T(r_{\rm m})\ r_{\rm m}^6} \tag{3}$$

Скорость турбулентных движений в оболочке, вызванных эффектом пропеллера:

$$V_{\rm t} \sim \Omega_{\rm s} R_{\rm m} \tag{4}$$

Вириальная температура:

$$T(r) \sim T_{\rm ff}(r) = (G M_{\rm ns} m_{\rm p})/(kr) \tag{5}$$

Радиус магнитосферы:

$$r_{\rm m} \equiv \left(\frac{\mu^2}{\dot{M}_{\rm c}\ \sqrt{2\ G\ M_{\rm ns}}}\right)^{2/7} \tag{6}$$

****

$$P_{\rm br} \simeq\ 450\ \mu_{30}^{16/21} \left(\frac{M_{\rm ns}}{M_{\odot}}\right)^{-4/21} \left(\frac{\dot{M}_{\rm c}}{10^{15}\,{\rm g\,s^{-1}}}\right)^{-5/7} {\rm c}$$

LPXPs Formation Scenario: Transition to Accretor at $P_{\rm max} \simeq P_{\rm br}$

Name	$\dfrac{<\dot{\mathfrak{M}}>}{<\dot{\mathfrak{M}}_{\rm x}>}$	$\dfrac{B_0}{B_{\rm cr}}$	$\dfrac{R_{\rm ns}}{10^6\ \text{см}}$
J170006-4157	1	0.08	1
0352+309/X Per	1	0.3	1
J1037.5-5647	1	0.3	1
J2239.3+6116	1	0.1	1
J0103.6-7201	1	0.9	1.3
J0146.9+6121/V831 Cas	1	0.3	1.3
2S 0114+650	1	1	1.3

CONCLUSIONS

★ LPXPs are Neutron Stars undergoing spherical accretion

★ Spin-down epoch contains four evolutionary states:

- **Ejector** →
  - **Supersonic propeller** →
    - **Subsonic propeller** →
      - **Accretor**

★ Assumption about supercritical MF of LPXPs is **not nesessary**

★ A question about the mechanism of accretion in LPXPs **is open**