Magnetic Accretion in Long-period X-ray Pulsars

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REFERENCES

1. Ikhsanov N.R., Pustil'nik, L.A. & Beskrovnaya, N.G. 2012 AIP Conf. Proc. **1439**, 237

2. Ikhsanov N.R. & Beskrovnaya, N.G. 2012 Astronomy Reports, in press (**arXiv:1205.2846**)

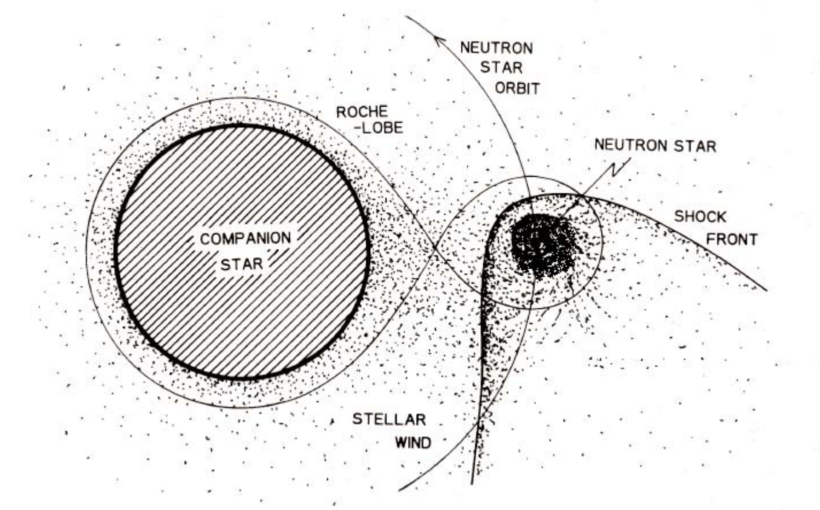
3. Ikhsanov N.R. & Finger, M.H. 2012 ApJ **751**, in press (**arXiv:1204.4975**)

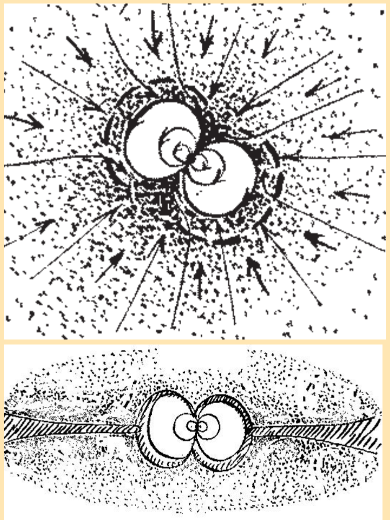
4. Ikhsanov N.R. 2012 MNRAS, in press

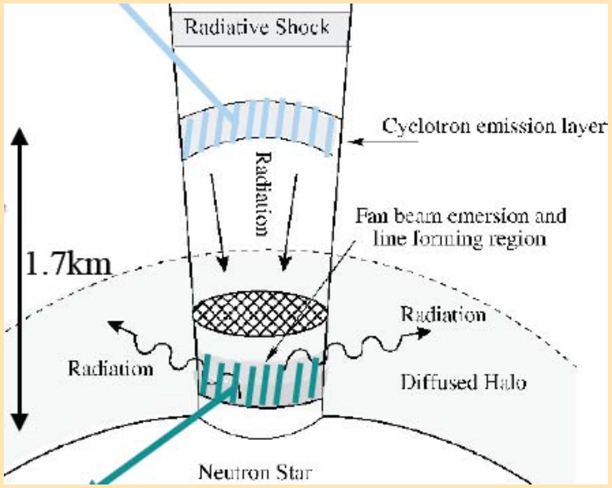
5. Ikhsanov N.R. & Pustil'nik, L.A. 2012 ApJ, submitted

6. Ikhsanov N.R. & Beskrovnaya, N.G. 2012 Astronomy Reports, submitted

Long-Period X-ray Pulsars (LPXPs)







Mass capture rate $\dot{\mathfrak{M}}_{\mathrm{c}} = \pi \, R_{\mathrm{G}}^2 \, \rho_\infty \, V_{\mathrm{rel}}$

Bondi radius $R_{\mathrm{G}} = \dfrac{2GM_{\mathrm{ns}}}{V_{\mathrm{rel}}^2}$

Relative velocity $V_{\mathrm{rel}} = V_{\mathrm{s}} + |\, \vec{V}_{\mathrm{orb}} + \vec{V}_{\mathrm{w}} \,|$

Corotation radius $R_{\mathrm{cor}} = \left(\dfrac{GM_{\mathrm{ns}}}{\omega_{\mathrm{s}}^2} \right)^{1/3}$

Alfvén radius $R_{\mathrm{A}} = \left(\dfrac{\mu^2}{\dot{\mathfrak{M}}_{\mathrm{c}} \, (2GM_{\mathrm{ns}})^{1/2}} \right)^{2/7}$

Mass accretion rate $\dot{\mathfrak{M}}_{\mathrm{a}} = \dfrac{L_{\mathrm{x}} R_{\mathrm{ns}}}{GM_{\mathrm{ns}}}$

Stationary accretion

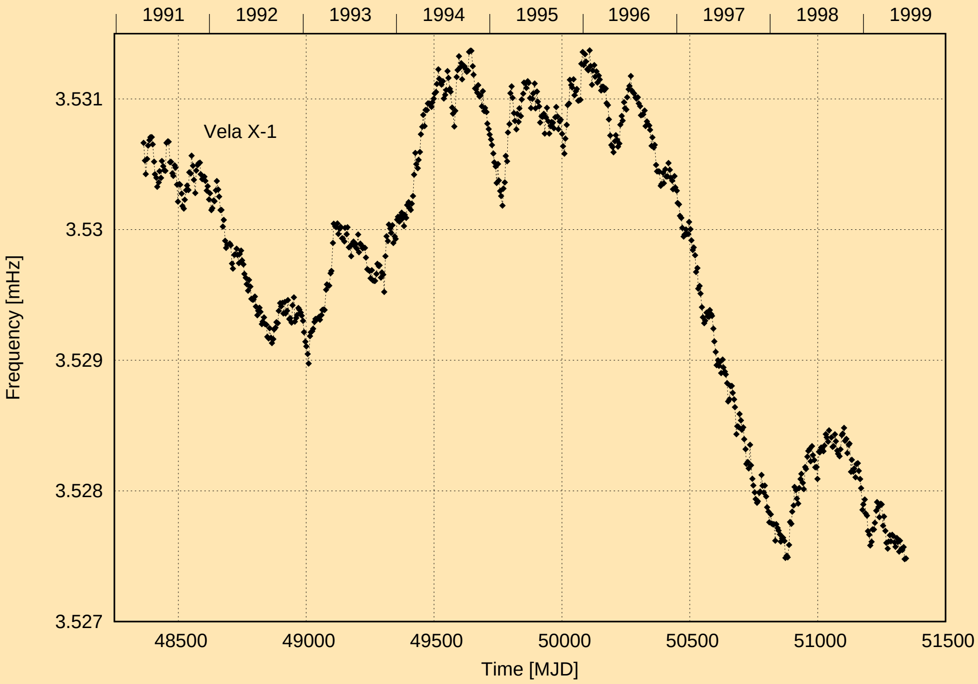
$$\dot{\mathfrak{M}}_{\mathrm{c}} = \dot{\mathfrak{M}}_{\mathrm{a}} \equiv \dot{\mathfrak{M}}$$

Persistent X-ray emitter

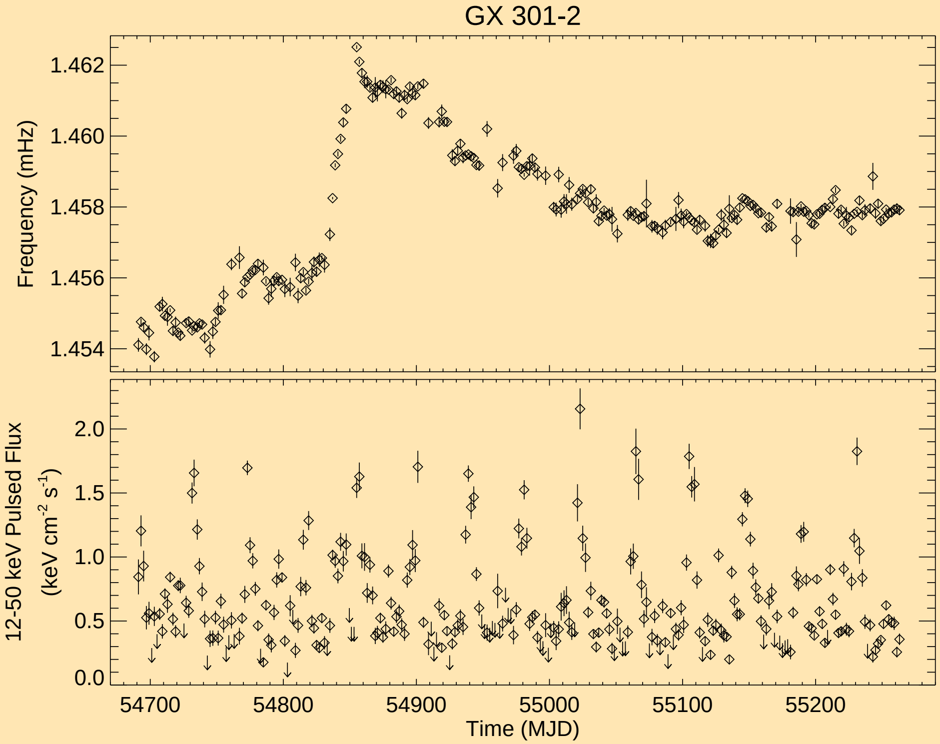
$$R_{\mathrm{m}} < R_{\mathrm{cor}}$$

Spin Evolution (Spin-up $\longleftrightarrow$ Spin-down)

Vela X–1



GX 301–2



Name	P_{s}, s	log L_{x}	E_{cyc}	$\dot{P}$, s/s	P_{orb}, d	Sp. type	d
Vela X–1	283	36.5	∼ 23 keV	[±] E − 6.8	9	B0.5 Ib	2 kpc
GX 301–2	683	37-37.5	∼ 35 keV	[±] E − 7.3	41.5	B1 Ia	1.8–3 kpc
X Persei	837	34.7–35.5	∼ 30 keV	[±] E − 5.5	250	B0 Ve	950 pc
SXP 1062	1062	35.8	–	[+] E − 5.5	300	B0 IIIe	62 kpc
4U 2206+54	5554	35–35.6	∼ 30 keV	[+] E − 6.3	19.25	O9e[shell]	2.6 kpc

Conventional Spin Evolution Scenario

$$2\pi I\dot{\nu} \;=\; K_{\rm su} \;+\; K_{\rm sd} \qquad \longrightarrow \qquad P_{\rm eq} \;\equiv\; P_{\rm s}\left(\,|K_{\rm su}| = |K_{\rm sd}|\,\right)$$

Spin-up torque

$$K_{\rm su} \;=\; \begin{cases} \dot{\mathfrak{M}}_{\rm a}\ \left(G M_{\rm ns}\ R_{\rm m}\right)^{1/2} & \text{Disk} \\ \dot{\mathfrak{M}}_{\rm a}\ \left[\Omega_{\rm orb}\ R_{\rm G}^{2}\right]\ \xi & \text{Quasi-Spherical} \end{cases}$$

Spin-down torque

$$K_{\rm sd} \;=\; -\,k_{\rm t}\,\frac{\mu^{2}}{R_{\rm cor}^{3}}$$

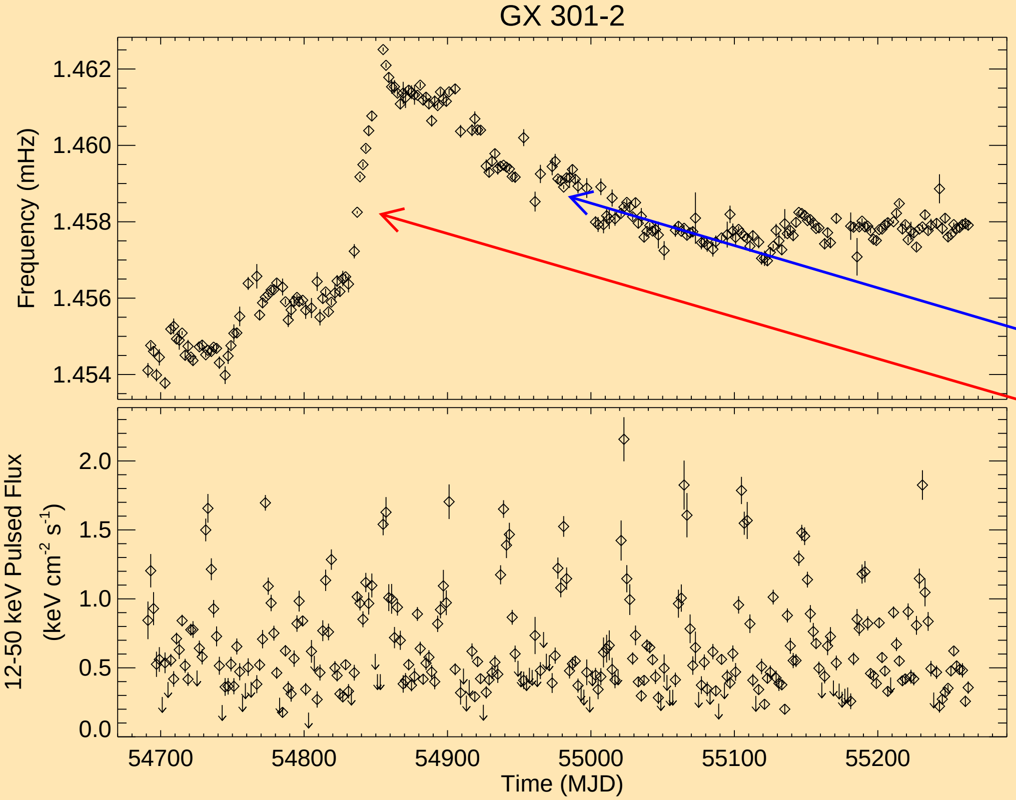
Name	$P_{\rm s}$, Observed	$P_{\rm eq}$, Disk	$P_{\rm eq}$, Quasi-spherical
Vela X–1	283 s	10 s	200 - 600 s
GX 301-2	683 s	4 s	50 - 150 s
X Persei	837 s	10 s	800 - 1000 s
4U 2206+54	5554 s	10 s	250 – 500 s

$$R_{\rm m} = R_{\rm A}$$

$$<\xi>= 0.2$$

$$\Omega_{\rm orb} = \frac{1}{P_{\rm orb}}$$

Spin Evolution of the LPXP GX 301–2



Spin period	$P_\mathrm{s} \simeq 675 - 700\,\mathrm{s}$
Relative velocity	$V_\mathrm{rel} \sim 250 - 600\,\mathrm{km/s}$
Mass accretion rate	$\dot{\mathfrak{M}} \simeq 10^{17}\,\mathrm{g/s}$
Spin-down trends	$< \dot{\nu}_\mathrm{sd} > \simeq -10^{-13}\,\mathrm{Hz\,s^{-1}}$
Rapid spin-up	$< \dot{\nu}_\mathrm{su} > \simeq 5 \times 10^{-12}\,\mathrm{Hz\,s^{-1}}$

$$|K_\mathrm{sd}| \gtrsim 2\pi I\,\dot{\nu}_\mathrm{sd} \quad \Rightarrow \quad \mu \gtrsim \left(\frac{2\pi I\,\dot{\nu}_\mathrm{sd}\,GM_\mathrm{ns}}{k_\mathrm{t}\,\omega_\mathrm{s}^2}\right)^{1/2}$$

$$|K_\mathrm{su}| \gtrsim 2\pi I\,\dot{\nu}_\mathrm{su} \quad \Rightarrow \quad R_\mathrm{A} \gtrsim \frac{4\pi^2 I^2\,\dot{\nu}_\mathrm{su}^2}{\dot{\mathfrak{M}}^2\,GM_\mathrm{ns}}$$

Magnetic field determination

	Spin-down phase			Spin-up phase	Cyclotron line
	$I \approx 10^{45}\,\mathrm{g\,cm^2}$	$P_\mathrm{s}=P_\mathrm{eq}$ $(< \xi > \approx 0.2)$		$I \approx 10^{45}\,\mathrm{g\,cm^2}$	
Name	$\lvert K_\mathrm{sd}\rvert \gtrsim 2\pi I\dot{\nu}_\mathrm{sd}$	Quasi-Spherical	Disc	$\lvert K_\mathrm{su}\rvert \gtrsim 2\pi I\dot{\nu}_\mathrm{su}$	CRSF
GX 301-2	$\gtrsim 2 \times 10^{14}\,\mathrm{G}$	$\gtrsim 2 \times 10^{14}\,\mathrm{G}$	$> 10^{15}\,\mathrm{G}$	$4 \times 10^{12}\,\mathrm{G}$	$4 \times 10^{12}\,\mathrm{G}$

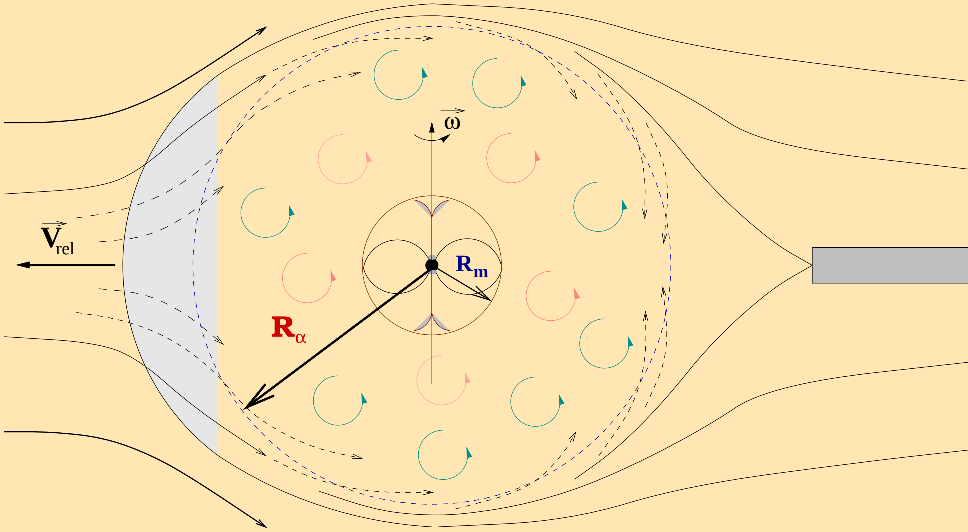
Can an accreting neutron star brake harder ?

(Non-magnetized accretion flow approximation)

$$\boxed{|K_{\rm sd}| \sim S_{\rm eff}\, \nu_{\rm t}\, \rho_0\, v_\phi}$$

$$|K_{\rm sd}| \sim \left[4\pi R_{\rm A}^2\right] \left[k_{\rm t}\, v_{\rm t}\, \ell_{\rm t}\right] \left[\frac{\dot{\mathfrak{M}}}{4\pi R_{\rm A}^2\, v_{\rm ff}(R_{\rm A})}\right] \left[\omega_{\rm s}\, R_{\rm A}\right] = k_{\rm t}\, v_{\rm t}\, \frac{\dot{\mathfrak{M}}\, \omega_{\rm s}\, R_{\rm A}^{5/2}}{(GM_{\rm ns})^{1/2}}$$

$\ell_{\rm t} \le R_{\rm A}$ $v_{\rm t} \le v_\phi = \omega_{\rm s}\, R_{\rm A}$	$\lvert K_{\rm sd}^{(0)}\rvert = \dfrac{k_{\rm t}\, \mu^2\, \omega_{\rm s}^2}{GM_{\rm ns}} \approx \dfrac{k_{\rm t}\, \mu^2}{R_{\rm cor}^3}$
$v_{\rm t} \le v_{\rm ff}(R_{\rm A})$	$K_{\rm sd}^{(\rm t)} = k_{\rm t}\, \dot{\mathfrak{M}}\, \omega_{\rm s}\, R_{\rm A}^2$



GX 301–2 brakes still harder:

$$\boxed{|\dot{\nu}| \le \frac{|K_{\rm sd}^{(\rm t)}|}{2\,\pi\, I} \sim 0.2\; k_{\rm t}\, |\dot{\nu}_{\rm sd}^{\rm obs}|}$$

Accretion from a magnetized flow $\left(\beta_0 = \dfrac{\mathcal{E}_{\rm th}(R_{\rm G})}{\mathcal{E}_{\rm m}(R_{\rm G})} \sim 1\right)$

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r–Ram $\mathcal{E}_{\rm ram}(R_{\rm G}) = \rho_\infty \, v_{\rm rel}^2$

ϕ–Ram $\mathcal{E}_{\rm rot}(R_{\rm G}) = \rho_\infty \, (\Omega_{\rm orb} \, R_{\rm G})^2$

Thermal $\mathcal{E}_{\rm th}(R_{\rm G}) = \rho_\infty \, c_{\rm s}^2(R_{\rm G})$

Magnetic $\mathcal{E}_{\rm m}(R_{\rm G}) = \dfrac{B_{\rm f}^2(R_{\rm G})}{8\pi}$

$$\mathcal{E}_{\rm ram}(r) = \mathcal{E}_{\rm ram}(R_{\rm G}) \left(\frac{R_{\rm G}}{r}\right)^{5/2}$$

$$\mathcal{E}_{\rm rot}(r) = \mathcal{E}_{\rm rot}(R_{\rm G}) \left(\frac{R_{\rm G}}{r}\right)^{7/2}$$

$$\mathcal{E}_{\rm m}(r) = {\beta_0}^{-1} \, \mathcal{E}_{\rm th}(R_{\rm G}) \left(\frac{R_{\rm G}}{r}\right)^{4}$$

Shvartsman radius

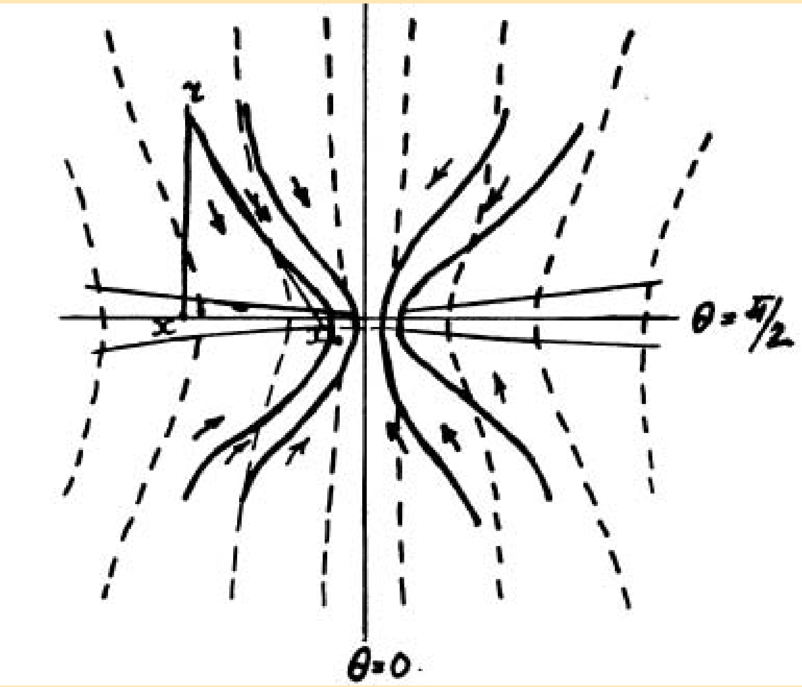
$$\mathcal{E}_{\rm m}(R_{\rm sh}) = \mathcal{E}_{\rm ram}(R_{\rm sh})$$

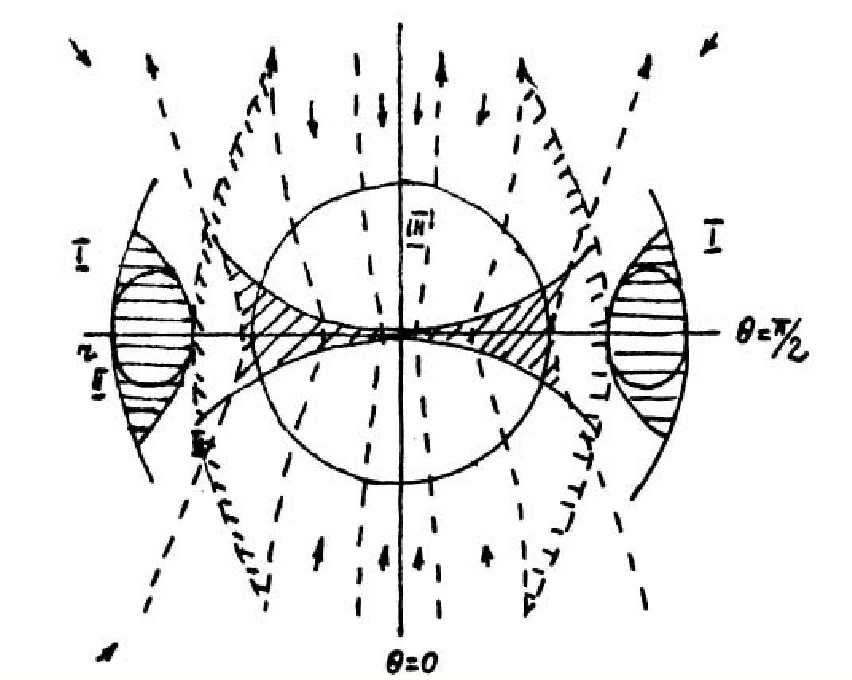
$$\boxed{R_{\rm sh} = \beta^{-2/3} \left(\frac{c_{\rm s}}{v_{\rm rel}}\right)^{4/3} R_{\rm G}}$$

Non-Keplerian Magnetic Slab

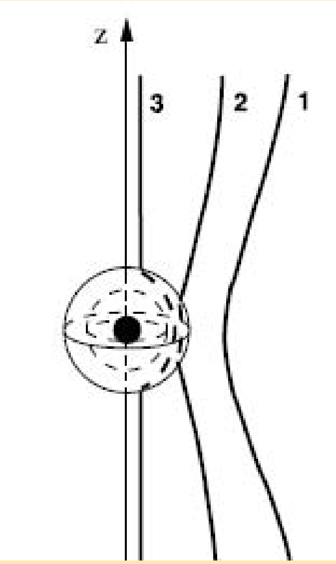
$$t_{\rm rec} = \frac{r}{\eta_{\rm m}\ v_{\rm A}} = \eta_{\rm m}^{-1}\ t_{\rm ff}\ \left(\frac{v_{\rm ff}}{v_{\rm A}}\right)$$

Bisnovatyi-Kogan & Ruzmaikin (1974, 1976)

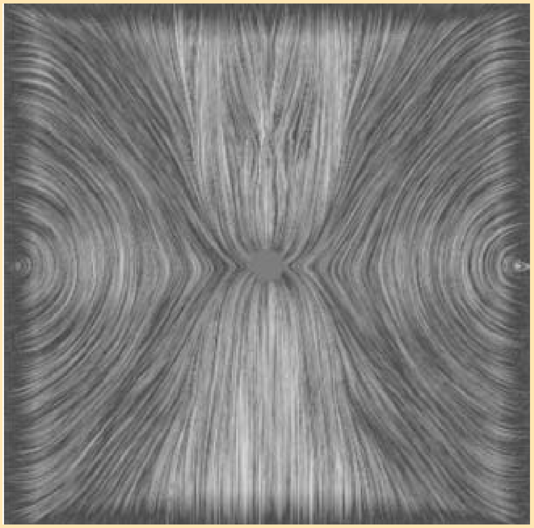




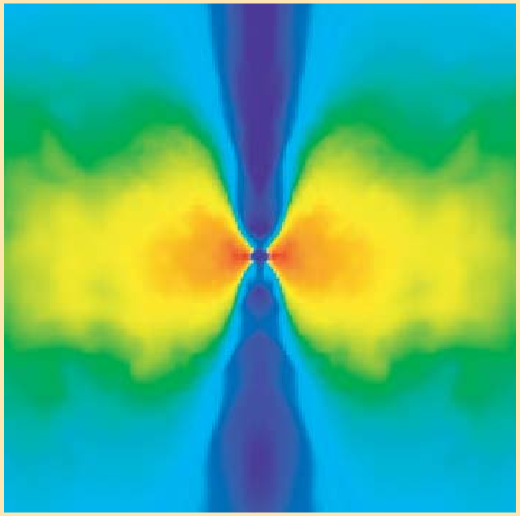
Igumenschev, Narayan & Abramowicz (2003)



Magnetic field



Density



Magnetic Accretion in X-ray Pulsars $v_{\rm br} < v_{\rm rel} < v_{\rm mca}$

$$R_{\rm sh} > R_{\rm A} \quad \rightarrow \quad v_{\rm rel} \lesssim \underline{v_{\rm mca} \simeq 760\,{\rm km\,s^{-1}}} \times \beta^{-1/5}\, m^{12/35}\, \dot{\mathfrak{M}}_{15}^{3/35}\, \mu_{30}^{-6/35} \left(\frac{c_{\rm s}}{10\,{\rm km\,s^{-1}}}\right)^{2/5}$$

$$R_{\rm circ} > R_{\rm sh} \quad \rightarrow \quad v_{\rm rel} < \underline{v_{\rm br} \simeq 100\,{\rm km\,s^{-1}}} \times \beta^{1/7}\, \xi_{0.2}^{3/7}\, m^{3/7}\, P_{40}^{-3/7} \left(\frac{c_{\rm s}}{10\,{\rm km\,s^{-1}}}\right)^{-2/7}$$

I.	Quasi-Spherical	$v_{\rm rel} > v_{\rm mca}$	Free-fall	$t_{\rm ff}$	Hot flow $(T(r_{\rm m}) \gtrsim 0.1\, T_{\rm ff})$
II.	Keplerian Disk	$v_{\rm rel} < v_{\rm cr}$	Viscousity	$t_{\rm visc}$	Cool flow $(T(r_{\rm m}) \ll 0.1\, T_{\rm ff})$
III.	Magnetic Accretion	$\boxed{v_{\rm cr} < v_{\rm rel} < v_{\rm mca}}$	Reconnection	$t_{\rm rec}$	Cool flow $(T(r_{\rm m}) \ll 0.1\, T_{\rm ff})$

Accretion from the non-Keplerian Magnetic Slab if $L_{\rm X} \gtrsim L_{\rm cr}$

$$\underline{L_{\rm cr} \simeq 3 \times 10^{34}\ {\rm erg\,s^{-1}}}\ \mu_{30}^{1/4}\, m^{1/2}\, R_6^{-1/8} \left(\frac{\eta_{\rm m}}{0.01}\right) \left(\frac{R_{\rm sh}}{R_{\rm A}}\right)^{1/2}$$

Spin-down torque applied to a Neutron Star from the Magnetic Slab

$$\boxed{|K_{\rm sd}^{\rm sl}| \;=\; S_{\rm eff}\;\nu_{\rm m}\;\rho_{\rm sl}(r_{\rm m})\;v_\phi(r_{\rm m})}$$

Effective Area	$S_{\rm eff} = 2\pi r_{\rm m} h_{\rm s}(r_{\rm m})$	Slab thickness	$h_{\rm s}(r_{\rm m}) = \dfrac{k_{\rm B} T_0 r_{\rm m}^2}{m_{\rm p} G M_{\rm ns}}$
M-Viscosity	$\nu_{\rm m} = k_{\rm m} r_{\rm m} v_{\rm A}(r_{\rm m})$		
ϕ–velocity	$v_\phi = r_{\rm m}\left[\omega_{\rm s} - \omega_{\rm sl}(r_{\rm m})\right]$	Slab density	$\rho_{\rm sl}(r_{\rm m}) = \dfrac{\mu^2\, m_{\rm p}}{2\pi\, k_{\rm B}\, T_0\, r_{\rm m}^6}$

$$\boxed{|K_{\rm sd}^{\rm sl}| = \frac{k_{\rm m}\,\mu^2}{r_{\rm m}^{3/2}}\left(\frac{1}{R_{\rm cor}^{3/2}} - \frac{\omega_{\rm sl}(r_{\rm m})}{(G M_{\rm ns})^{1/2}}\right)}$$

$$|K_{\rm sd}^{\rm max}| = \frac{k_{\rm m}\,\mu^2}{(R_{\rm m}\;R_{\rm cor})^{3/2}}$$

Magnetospheric Radius

I. **Interchange instabilities:**

$$\left[\, \dot{\mathfrak{M}}_{\rm in}(R_{\rm A}) \equiv \dot{\mathfrak{M}}_{\rm c} \,\right]$$

$$[\, R_{\rm m} \;=\; R_{\rm A} \,]$$

$$\longrightarrow \quad \underline{|K_{\rm sd}^{\rm sl}(R_{\rm A})| \;=\; k_{\rm m}\, \dot{\mathfrak{M}}\, \omega_{\rm s}\; R_{\rm A}^2}$$

II. **Bohm Diffusion:**

$$\dot{\mathfrak{M}}_{\rm in}(r_{\rm m}) = 4\pi r_{\rm m}\; \delta_{\rm m}(r_{\rm m})\; \rho_{\rm sl}(r_{\rm m})\; v_{\rm ff}(r_{\rm m}) \propto\; r_{\rm m}{}^{-13/4}$$

Stationary accretion:

$$\dot{\mathfrak{M}}_{\rm in}(R_{\rm ma}) = \frac{L_{\rm X} R_{\rm ns}}{G M_{\rm ns}} = \dot{\mathfrak{M}}_{\rm c}$$

Plasma accumulation

$$\boxed{R_{\rm ma} \simeq 8 \times 10^7\ {\rm cm} \times \alpha_{0.1}^{2/13}\ \mu_{30}^{6/13}\ T_6^{-2/13}\ m^{5/13}\ L_{37}^{-4/13}\ \left(\frac{R_{\rm ns}}{10\,{\rm km}}\right)^{-4/13}}$$

GX 301–2:

$$|\, \dot{\nu}_{\rm sd}^{\rm (ma)} \,| \;=\; \frac{|\, K_{\rm sd}^{\rm sl}(R_{\rm ma}) \,|}{2\pi I} \;\sim\; |\, \dot{\nu}_{\rm sd}^{\rm (obs)} \,| \left(\frac{k_{\rm m}}{0.14}\right)$$

Spin-down at the observed rate !

Magnetic Accretion Picture

1. Accretion from a magnetized wind $\left(\beta_0 \sim 1\right)$
2. Deceleration of the free-falling material at the Shvartsman radius $R_{\rm sh}$
3. Formation of the non-Keplerian magnetic slab
4. Accumulation and diffusion of material into the NS's magnetic field
5. Stationary accretion at $\dot{\mathfrak{M}}_{\rm diff}(R_{\rm ma}) = \dfrac{L_{\rm X} R_{\rm ns}}{G M_{\rm ns}}$

New parameters:

Shvartsman radius: $R_{\rm sh}$

Magnetospheric radius: $R_{\rm ma}$

Spin-down torque: $|\,K_{\rm sd}^{\rm sl}\,| = \dfrac{k_{\rm m}\,\mu^2}{R_{\rm ma}^{3/2}} \left(\dfrac{1}{R_{\rm cor}^{3/2}} - \dfrac{\omega_{\rm sl}(R_{\rm ma})}{(G M_{\rm ns})^{1/2}} \right)$

Magnetic Accretion in young Be/X-ray Pulsar SXP 1062

Associated with a SNR of the age $\tau \sim (1-4) \times 10^4\,\mathrm{yr}$

Persistent accretion-powered Pulsar $R_\mathrm{m} < R_\mathrm{cor}$

Name	P_s, s	$\log L_\mathrm{x}$	E_cyc	$\dot{\nu}$, Hz/s	P_orb, d	Sp. type	d
SXP 1062	1062	35.8	–	-2.6×10^{-12}	300	B0 IIIe	62 kpc

Magnetic field determination

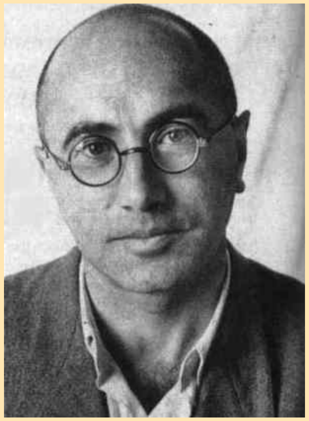
Spin-down torque	Magnetic field	Magnetospheric radius
$\frac{\mu^2}{R_\mathrm{cor}^3} \geq 2\pi I \dot{\nu}_\mathrm{obs}$	$B_* \geq 6 \times 10^{14}\,\mathrm{G}$	$R_\mathrm{A} > R_\mathrm{cor}$
$\dot{\mathfrak{M}}\, \omega_\mathrm{s}\, R_\mathrm{A}^2 \geq 2\pi I \dot{\nu}_\mathrm{obs}$	$B_* \geq 10^{15}\,\mathrm{G}$	$R_\mathrm{A} > R_\mathrm{cor}$
$\frac{\mu^2}{(R_\mathrm{ma}\, R_\mathrm{cor})^{3/2}} \geq 2\pi I \dot{\nu}_\mathrm{obs}$	$B_* \geq 4 \times 10^{13}\,\mathrm{G}$	$R_\mathrm{ma} \sim 0.01\, R_\mathrm{cor}$

Spin Evolution of SXP 1062

Name	$P_{\rm s}$, s	$\log L_{\rm x}$	B_*	$\dot\nu$, Hz/s	$P_{\rm orb}$, d	Sp. type	d
SXP 1062	1062	35.8	4×10^{13} G	-2.6×10^{-12}	300	B0 IIIe	62 kpc

Ejector phase *(Spin-powered pulsar)*	**Magneto-dipole (conv.)**	$\tau \sim 6 \times 10^4$ yr
	Spitkovsky (2006)	$\tau \sim 2 \times 10^4$ yr
	Beskin et al. (1993)	$\tau \sim 10^4$ yr
Propeller phase	$\tau_{\rm prop} \sim \dfrac{\pi I R_{\rm ma}^3}{\mu^2 \, P_{\rm prop}}$	$\tau_{\rm prop} \sim 2300$ yr
Accretor phase	$\tau_{\rm acc} \sim \dfrac{1}{2 \mid \dot\nu_{\rm obs} \mid P_{\rm prop}}$	$\tau_{\rm acc} \sim 600$ yr

Age of the Pulsar is $\tau \sim (2-4) \times 10^4$ yr



Final Remarks

- **Spin evolution of LPXPs can be explained in terms of Magnetic Accretion Scenario.**
- **No assumptions** about **peculiar properties** of NS and their Magnetic Field **are required**.
- **Diffusion-driven accretion** (the magnetospheric boundary can be **interchange stable**)

A Farewell to Accreting Magnetars...

Welcome to Magnetic Accretion