Spin Evolution of Pulsars

CHALLENGES

Conventional Accretion Scenarios

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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, **56, 589**
3. Ikhsanov N.R. & Finger, M.H. 2012 ApJ, **753**, 1
4. Ikhsanov N.R. 2012 MNRAS, **424**, L39
5. Ikhsanov N.R., Pustil'nik, L.A. & Beskrovnaya, N.G. 2012 J. of Phys., Conf. Ser., **372**, 012062
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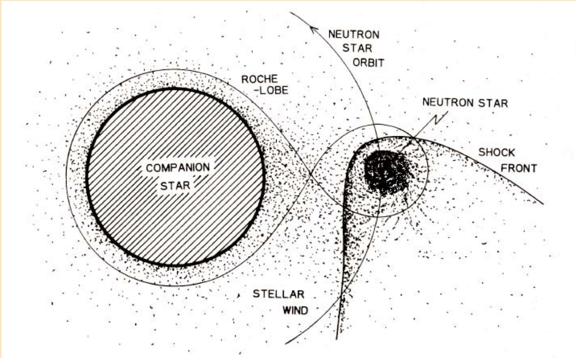
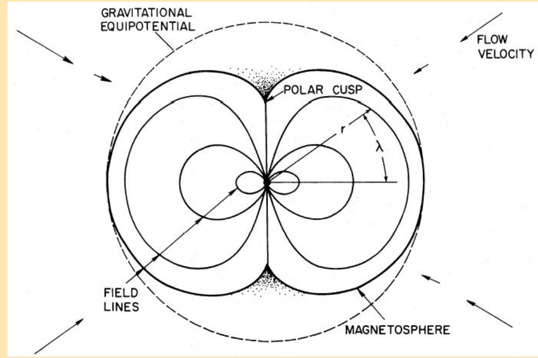
8. Ikhsanov N.R., Likh, Y.S., & Beskrovnaya, N.G. 2014 IJMP Conf. Ser., 28, id. 1460187
9. Ikhsanov N.R., Likh, Y.S., & Beskrovnaya, N.G. 2014 Astronomy Reports, **58**, 376

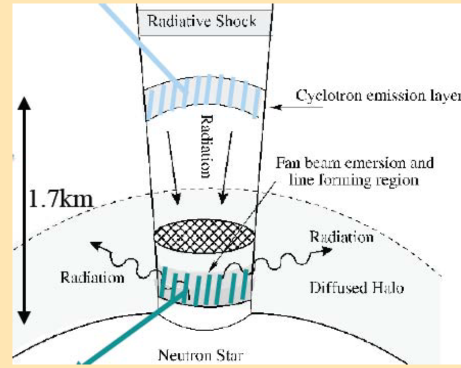
Long-Period X-ray Pulsars

Name	P_s, s	P_orb, d	L_{36} erg/s	B_{12} G	Sp. class	d, kpc
Vela X-1	283	9	4	2.6	B0.5 Ib	2
4U 1907+09	441	8	2	2.1	O8-9 Ia	4
GX 301-2	685	41.5	10	4	B1 Ia	3
X Persei	837	250	0.1	3.3	B0 Ve	1

Accretion-powered pulsars in wind-fed HMXBs







- NS captures gas at the Bondi radius $r_{\rm G} = \dfrac{2GM_{\rm ns}}{V_{\rm rel}^2}$

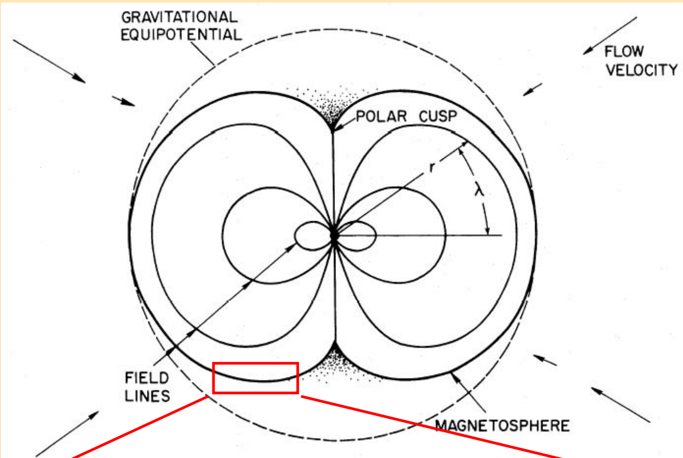
- The gas is decelerated at the Alfvén radius $r_{\rm A} = \left(\dfrac{\mu^2}{\dot{\mathfrak{M}}(2GM_{\rm ns})^{1/2}}\right)^{2/7}$

- **Accretion flow penetrates into the stellar magnetic field**

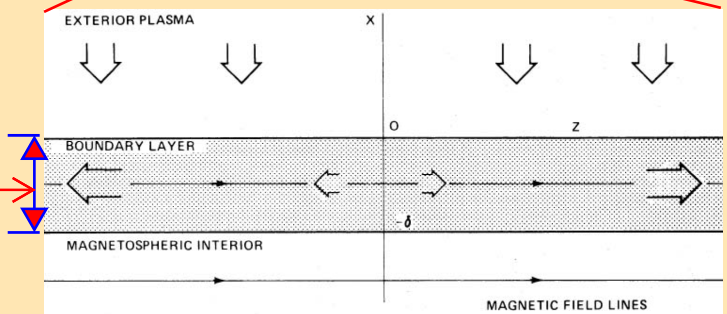
- X-ray luminosity $L_{\rm X} = \dot{\mathfrak{M}}\,\dfrac{GM_{\rm ns}}{R_{\rm ns}}$

- Surface magnetic field $B_{\rm CRSF} \le 10^{12} \left(\dfrac{E_{\rm cyc}}{11.6\,{\rm keV}}\right)\,{\rm G}$

Diffusion of the accreting material into the stellar field



$$\dot{\mathfrak{M}}_{\rm diff}(r_{\rm m}) = \begin{cases} \dfrac{L_{\rm X} R_{\rm ns}}{G M_{\rm ns}} \\[2em] 4\pi r_{\rm m}\ \delta_{\rm m}(r_{\rm m})\ \rho(r_{\rm m})\ v_{\rm ff}(r_{\rm m}) \end{cases}$$



$$\dot{\mathfrak{M}}_{\rm diff} \sim \frac{\mu^2\ D_{\rm eff}^{1/2}}{(G M_{\rm ns})^{3/4}} \left(\frac{c_{\rm s}(r_{\rm m})}{v_{\rm ff}(r_{\rm m})}\right)^{-2} \left[\ \mathbf{r}_{\rm m}\ \right]^{-15/4}$$

$$\delta_{\rm m}(r_{\rm m}) = \Big[t_{\rm ff}(r_{\rm m})\ D_{\rm eff}(r_{\rm m})\Big]^{1/2}$$

$$\boxed{D_{\rm eff}(r_{\rm A})\ \sim\ 10^{17}\ {\rm cm^2\,s^{-1}}\ \times\ \mu_{30}^{2/7}\ m^{3/7}\ \dot{\mathfrak{M}}_{15}^{1/7}\ \left(\frac{c_{\rm s}(r_{\rm A})}{v_{\rm ff}(r_{\rm A})}\right)^4}$$

Penetration Problem

Coulomb diffusion $$D_c = \frac{c^2}{4\pi\sigma} \sim 2 \times 10^{-16} \; D_{\rm eff}(r_A)$$

Bohm diffusion $$D_B = \frac{c\, k_B\, T_i(r_m)}{16\, e\, B(r_m)} \sim 3 \times 10^{-10} \; D_{\rm eff}(r_A)$$

Possible solutions

- **Magnetospheric boundary is interchange unstable**

  (Arons & Lea 1976, 1980; Elsner & Lamb 1976, 1977, 1984)

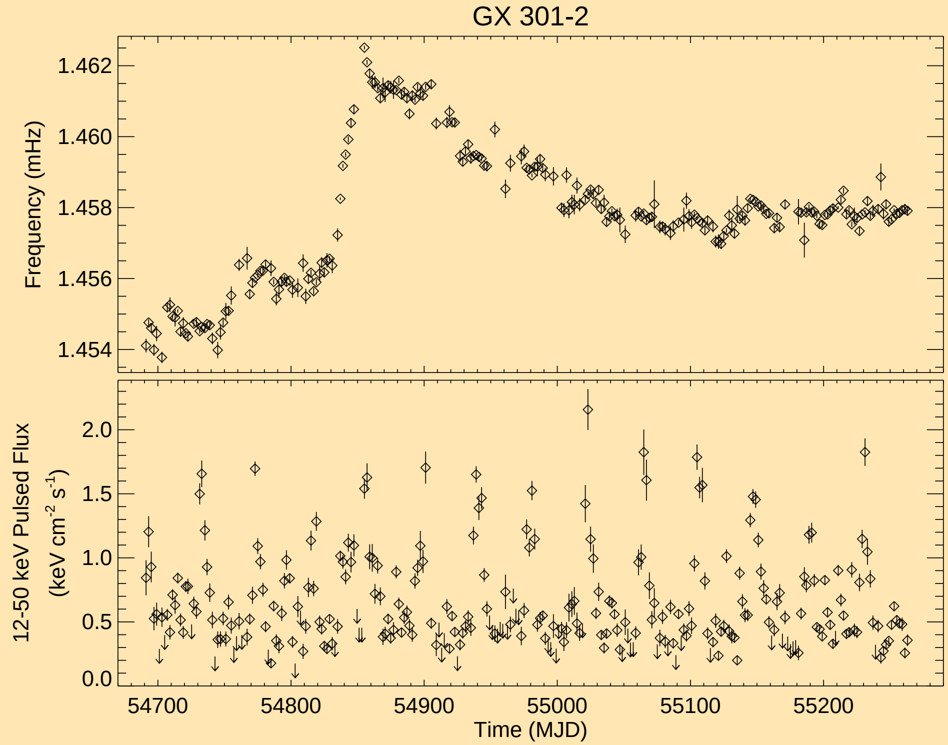
- **The accretion flow differs from the spherically symmetrical**
  - the accretion flow is cool $\longrightarrow$ $c_s(r_m) \ll v_{\rm ff}(r_m)$
  - its pressure at r_m exceeds the ram pressure $\longrightarrow$ $r_m < r_A$

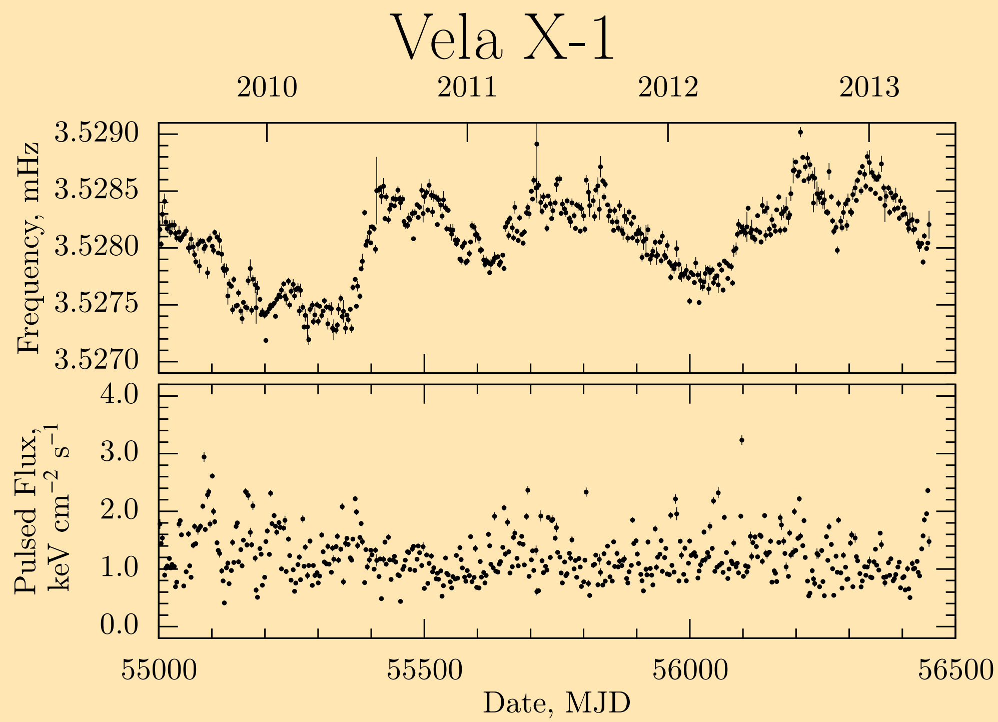
Penetration problem

Spin evolution of

X-ray Pulsars

Spin Evolution of X-ray Pulsars





$$\boxed{2\pi\, I\, \dot{\nu} \;=\; K_{\rm su} \;-\; K_{\rm sd}}$$

$$|K_{\rm sd}| \;\geq\; 2\pi\; I\; |\dot{\nu}_{\rm sd}| \qquad\qquad |K_{\rm su}| \;\geq\; 2\pi\; I\; |\dot{\nu}_{\rm su}|$$

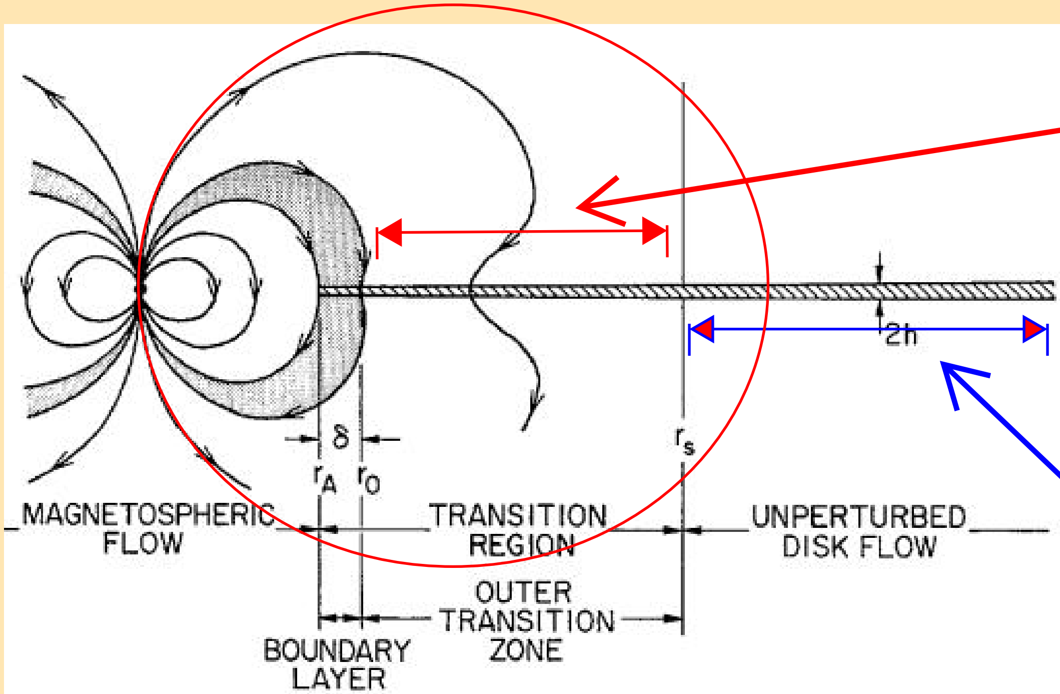
$$\boxed{P_{\rm eq} \;\equiv\; P_{\rm s}\,(K_{\rm su} = K_{\rm sd})}$$

Accretion Scenario Modeling Constrains

- Equilibrium period $\quad P_{\rm eq} \;\geq\; (\gg)\; 100\,{\rm s}$

- Spin-down torque $\quad |K_{\rm sd}| \;\geq\; 2\pi\; I\; |\dot{\nu}_{\rm sd}^{\rm obs}|$

Keplerian Disk: Are LPXPs Magnetars?



Spin-up torque:

$$|K_{\rm su}| = \dot{\mathfrak{M}}\ (G M_{\rm ns}\ r_{\rm A})^{1/2}$$

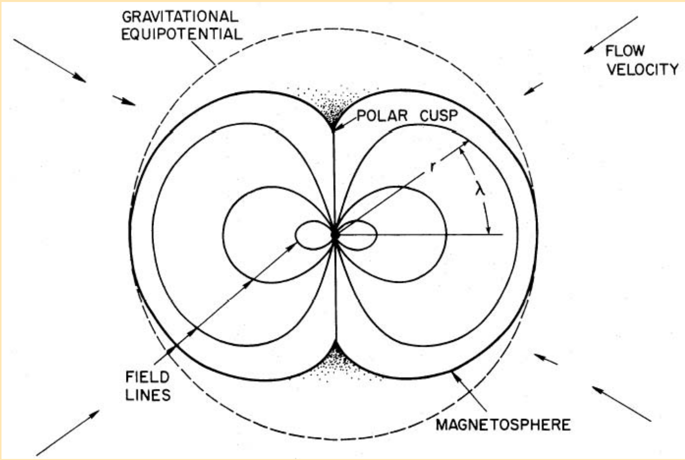
Spin-down torque:

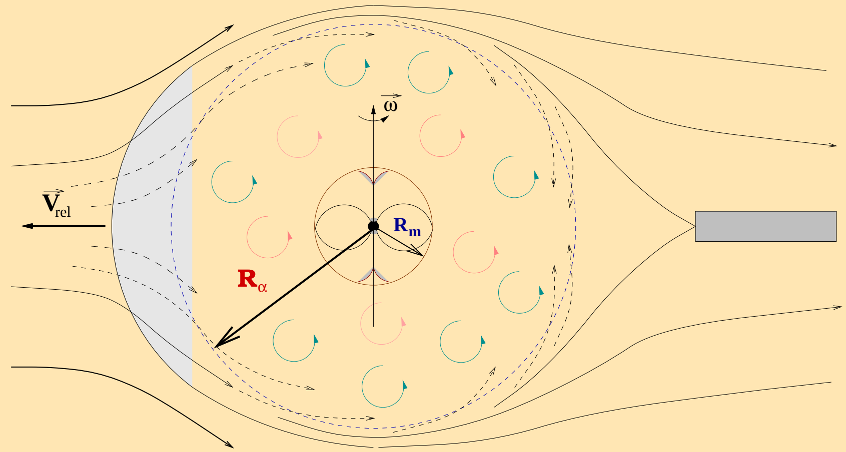
$$|K_{\rm sd}| = k_{\rm t}\ \frac{\mu^2}{r_{\rm cor}^3}$$

Equilibrium period: $$P_{\rm eq}^{\rm (Kd)} = 2.5\,{\rm s} \times k_{\rm t}^{3/2}\ m^{-5/7}\ \left(\frac{\mu}{10^{30}\,{\rm G\,cm^3}}\right)^{6/7} \left(\frac{\dot{\mathfrak{M}}}{10^{17}\,{\rm g\,s^{-1}}}\right)^{-3/7}$$

$$\frac{P_{\rm eq}^{\rm (Kd)}}{P_{\rm s}^{\rm obs}} \sim 10^{-2} - 10^{-3}\ \left(\frac{\mu}{10^{30}\,{\rm G\,cm^3}}\right)^{6/7}$$

Quasi-spherical accretion: Are LPXPs Magnetars?





$$|\dot{\nu}_{\rm sd}^{(0)}| \le \frac{1}{2\pi I}\left[k_{\rm t}\,\frac{\mu^2}{r_{\rm cor}^3}\right]$$

$$|\dot{\nu}_{\rm sd}^{(\rm t)}| \le \frac{1}{2\pi I}\left[k_{\rm t}\,\dot{\mathfrak{M}}\,\omega_{\rm s}\,r_{\rm A}^2\right]$$

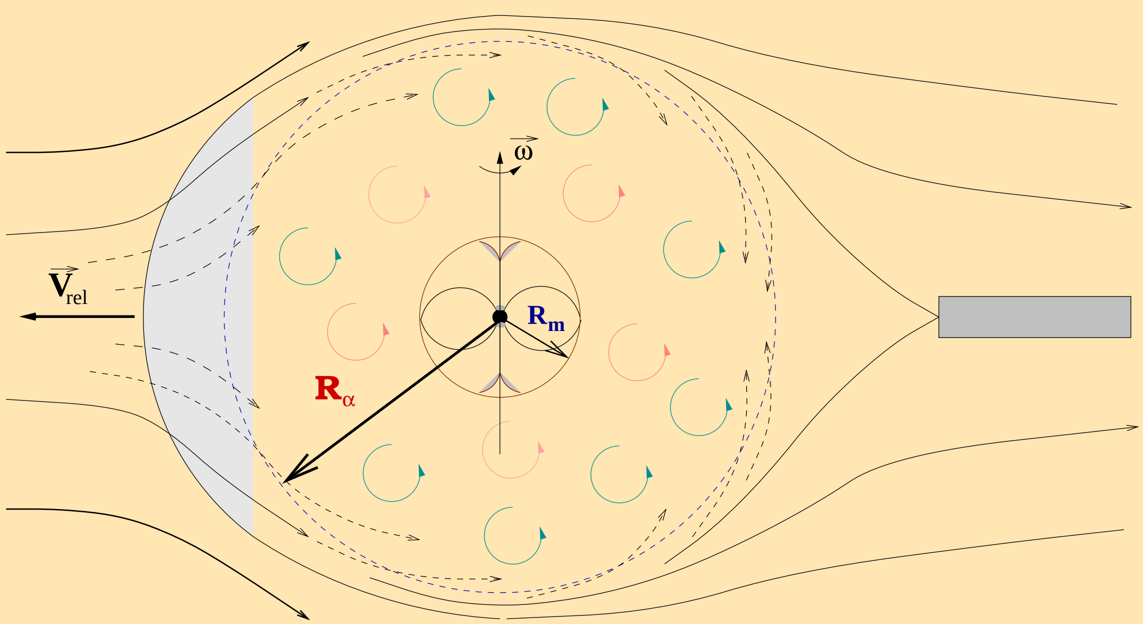
Name	B_{12}, G	$P_{\rm s}$, s	$\left| \dot{\nu}_{\rm sd}^{(0)} / \dot{\nu}_{\rm sd}^{\rm obs} \right|$	$\left| \dot{\nu}_{\rm sd}^{(\rm t)} / \dot{\nu}_{\rm sd}^{\rm obs} \right|$
Vela X-1	2.6	283	0.003	0.08
4U 1907+09	2.1	438	0.05	0.24
GX 301-2	4.0	683	0.003	0.23
X Persei	3.3	837	0.05	0.09

Torque definition

$$\mathbf{K} = \mathbf{r} \times \mathbf{F}$$

Model task:

A sphere of the radius r_{m}
is rotating in a viscose medium



Torque exerted on a NS at its magnetosphere

$$K(r_{\rm m}) \;=\; \nu_{\rm t}\; S_{\rm eff}(r_{\rm m})\; \rho(r_{\rm m})\; v_{\phi}(r_{\rm m})$$

Viscosity $\nu_{\rm t} = k_{\rm t}\;\ell_{\rm t}\, v_{\rm t}$

Effective Area $S_{\rm eff} = 2\pi r_{\rm m} \left(\dfrac{c_{\rm s}^2(r_{\rm m})\; r_{\rm m}^2}{GM_{\rm ns}}\right)$

Density $\rho(r_{\rm m}) = \dfrac{1}{c_{\rm s}^2(r_{\rm m})}\left(\dfrac{\mu^2}{2\pi\, r_{\rm m}^6}\right)$

ϕ–velocity $v_{\phi} = r_{\rm m}\;\left[\omega_{\rm s} - \Omega(r_{\rm m})\right]$

$$\ell_{\rm t} \;\le\; r_{\rm m}$$

$$v_{\rm t} \;\le\; v_{\rm k}(r_{\rm m})$$

$$r_{\rm cor} = \left(\frac{GM_{\rm ns}}{\omega_{\rm s}^2}\right)^{1/3}$$

$$\boxed{K(r_{\rm m}) \;=\; k_{\rm t}\, \frac{\mu^2}{(r_{\rm m}\, r_{\rm cor})^{3/2}} \left(1 - \frac{\Omega(r_{\rm m})}{\omega_{\rm s}}\right)}$$

Ikhsanov, N.R. & Beskrovnaya, N.G. Astronomy Reports, 56, 589 (2012)
Ikhsanov, N.R. & Finger, M.H. Astrophysical Journal, 753, 1 (2012)
Ikhsanov, N.R., Kim, V.Yu., Beskrovnaya, N.G. & Pustil'nik, L.A. ApSS, 346, 105 (2013)

Correspondence principle is satisfied

$$\boxed{|K_{\rm sd}(r_{\rm m})| \ \le \ \frac{\mu^2}{(r_{\rm m}\ r_{\rm cor})^{3/2}}\left(1 - \frac{\Omega(r_{\rm m})}{\omega_{\rm s}}\right)}$$

I. Accretion from a Turbulent-dominated Atmosphere

$$\Omega(r_{\rm m}) \ = \ 0$$

$$\boxed{r_{\rm m} \ \equiv \ r_{\rm A} = \left(\frac{\mu^2}{\dot{\mathfrak{M}}\sqrt{2GM_{\rm ns}}}\right)^{2/7}}$$

$$v_{\rm t}(r_{\rm A}) = v_{\rm k}(r_{\rm A})$$

$$|K_{\rm sd}^{\rm (t)}(r_{\rm A})| \ \le \ \dot{\mathfrak{M}}\,\omega_{\rm s}\,r_{\rm A}^2$$

II. Accretion from a free-falling material (Bondi accretion scenarios)

$$\Omega(r_{\rm m}) \ = \ 0$$

$$r_{\rm m} \ \equiv \ r_{\rm A}$$

$$\boxed{v_{\rm t}(r_{\rm A}) = \omega_{\rm s}\,r_{\rm A}}$$

$$|K_{\rm sd}^{\rm (ff)}(r_{\rm A})| \ = \ |K_{\rm sd}^{\rm (t)}(r_{\rm A})| \times \left(\frac{\omega_{\rm s}\,r_{\rm A}}{v_{\rm k}}\right) \ \le \ \frac{\mu^2}{r_{\rm cor}^3}$$

Ikhsanov N.R. 2012, MNRAS, 424, L39

Evaluation of the Magnetospheric Radius from Spin Evolution

$$|K_{\rm sd}| = \frac{k_{\rm t}\ \mu^2}{(r_{\rm m}\ r_{\rm cor})^{3/2}} \geq 2\pi I\,|\dot{\nu}_{\rm sd}^{\rm obs}|$$

$$\boxed{r_{\rm m} \leq \left(\frac{k_{\rm t}\ \mu^2}{2\pi I|\dot{\nu}_{\rm sd}^{\rm obs}|}\right)^{2/3} \left(\frac{\omega_{\rm s}^2}{GM_{\rm ns}}\right)^{1/3}}$$

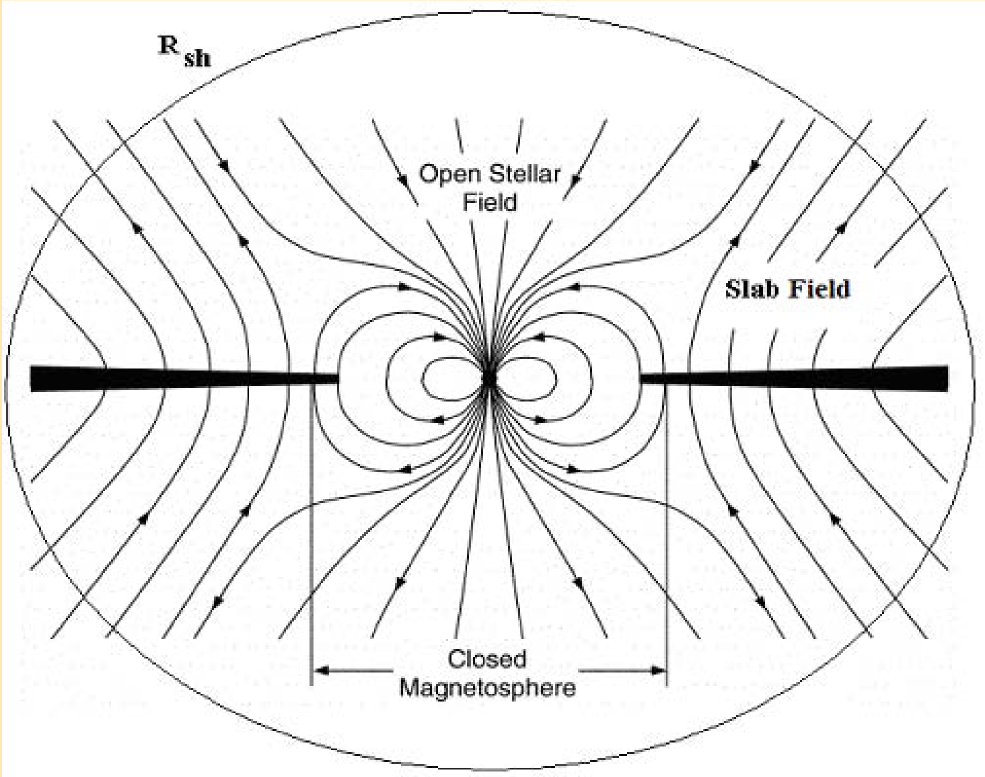
Name	B_{12}, G	$P_{\rm s}$, s	$\lvert\dot{\nu}_{\rm sd}\rvert$, 10^{-13} Hz/s	$r_{\rm m}$, 10^8 cm	$r_{\rm A}$, 10^8 cm	$r_{\rm m}/r_{\rm A}$
Vela X-1	2.6	283	3	1.5	8.3	0.18
4U 1907+09	2.1	438	0.4	2.9	6	0.48
GX 301-2	4	683	1	1.9	5.5	0.34
X Persei	3.3	837	0.24	4.5	23	0.2

$$\boxed{r_{\rm m} \leq (0.2 - 0.5)\ r_{\rm A}}$$

Penetration problem $\longrightarrow$ $r_{\mathrm{m}} < r_{\mathrm{A}}$

Spin evolution of LPXPs $\longrightarrow$ $r_{\mathrm{m}} < r_{\mathrm{A}}$

- Quasi-spherical Accretion $r_{\mathrm{m}} \geq r_{\mathrm{A}}$
- Keplerian Disk Accretion $P_{\mathrm{eq}} \ll P_{\mathrm{obs}}$
- Magnetic-Levitation Accretion: (wind-fed accretion from a magnetized gas)



Magnetic-Levitation Accretion (MLA) in X-ray Pulsars

Basic condition: $\boxed{R_{\rm sh} > \max\{r_{\rm A}, r_{\rm circ}\}} \longrightarrow v_{\rm cr} < v_{\rm rel} < v_{\rm ma}$

$$v_{\rm ma} \simeq 465\,{\rm km\,s^{-1}} \times \beta_0^{-1/5}\,\mu_{30}^{-6/35}\,m^{12/35}\,\dot{\mathfrak{M}}_{15}^{3/35}\left(\frac{c_{\rm s}(r_{\rm G})}{10\,{\rm km\,s^{-1}}}\right)^{2/5}$$

$$v_{\rm cr} \simeq 100\,{\rm km\,s^{-1}} \times \beta_0^{1/7}\,\xi_{0.2}^{3/7}\,m^{3/7}\,P_{40}^{-3/7}\left(\frac{c_{\rm s}(r_{\rm G})}{10\,{\rm km\,s^{-1}}}\right)^{-2/7}$$

Three possible accretion scenarios

Quasi-spherical $\longleftarrow$ $v_{\rm rel} > v_{\rm ma}$

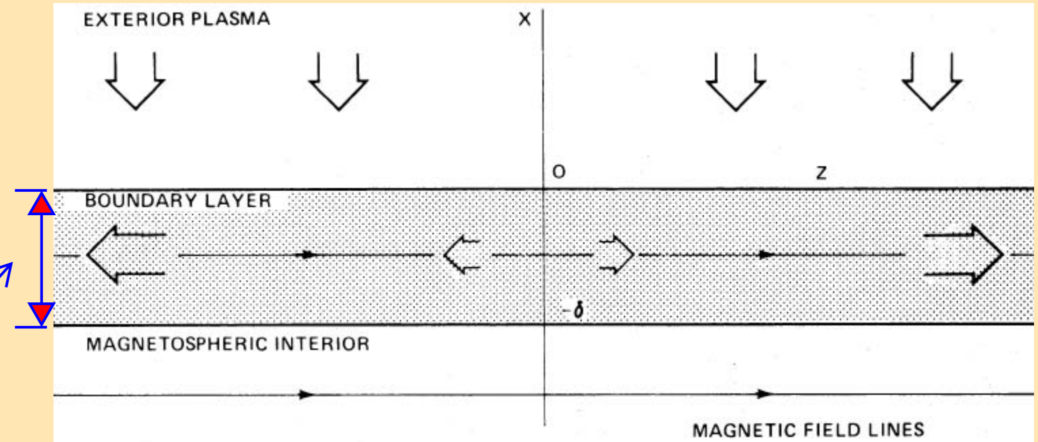
Keplerian disk $\longleftarrow$ $v_{\rm rel} < v_{\rm cr}$

MAGLEV Disk $\longleftarrow$ $v_{\rm cr} < v_{\rm rel} < v_{\rm ma}$

Ikhsanov & Beskrovnaya, Astronomy Reports, 56, 589 (2012)
Ikhsanov, Kim, Beskrovnaya & Pustilnik, ApSS, 346, 105 (2013)
Ikhsanov, Likh & Beskrovnaya, Astronomy Reports, 58, 376 (2014)

Magnetospheric radius of a neutron star in MLA- scenario

$$\begin{cases} \dfrac{\mu^2}{2\pi r_{\rm ma}^6} = \rho(r_{\rm ma})\, c_{\rm s}^2(r_{\rm ma}) \\ \dot{\mathfrak{M}}_{\rm in}(r_{\rm ma}) = \dfrac{L_{\rm X} R_{\rm ns}}{G M_{\rm ns}} \\ \dot{\mathfrak{M}}_{\rm in}(r_{\rm ma}) = 4\pi\, r_{\rm ma}\, \delta_{\rm m}\, \rho(r_{\rm ma})\, v_{\rm ff}(r_{\rm ma}) \\ \underline{\delta_{\rm m}(r_{\rm ma}) = \left[t_{\rm ff}(r_{\rm ma})\ D_{\rm eff}(r_{\rm ma})\right]^{1/2}} \end{cases}$$



$$D_{\rm eff}(r_{\rm ma}) = \alpha\, D_{\rm B}(r_{\rm ma}) = \alpha\, \frac{c k_{\rm B} T_{\rm i}(r_{\rm ma})}{16 e B(r_{\rm ma})}$$

$$\boxed{r_{\rm ma} = \left(\frac{c\, m_{\rm p}^2}{16\sqrt{2}\, e\, k_{\rm B}}\right)^{2/13} \frac{\alpha^{2/13}\ \mu^{6/13}\ (G M_{\rm ns})^{5/13}}{T_0^{2/13}\ L_{\rm X}^{4/13}\ R_{\rm ns}^{4/13}}}$$

Spin-down rates of LPXPs $\quad \left|\dot{\nu}_{\rm sd}^{\rm max}\right| \times 10^{-12}\,{\rm Hz\,s^{-1}}$

Name	B_{12}, G	$P_{\rm s}$, s	$\left\lvert\dot{\nu}_{\rm sd}^{\rm obs}\right\rvert$	$\left\lvert\dot{\nu}_{\rm sd}^{(0)}\right\rvert$	$\left\lvert\dot{\nu}_{\rm sd}^{(t)}\right\rvert$	$\left\lvert\dot{\nu}_{\rm sd}^{(m)}\right\rvert$
OAO 1657-415	3.2	38	3.2	0.056	0.18	3.3
Vela X-1	2.6	283	0.2	0.0003	0.012	0.4
4U 1907+09	2.1	438	0.04	0.0002	0.008	0.2
4U 1538-522	1.8	529	0.06	0.0002	0.008	0.15
GX 301-2	4	683	0.1	0.003	0.02	0.7
X Persei	3.3	837	0.024	0.0001	0.0013	0.03

$$\left|\dot{\nu}^{(0)}\right| = \frac{1}{2\pi I}\left[\frac{\mu^2}{r_{\rm cor}^3}\right]; \qquad \left|\dot{\nu}^{(t)}\right| = \frac{1}{2\pi I}\left[\dot{\mathfrak{M}}\,\omega_{\rm s} R_{\rm A}\right]; \qquad \left|\dot{\nu}^{(m)}\right| = \frac{1}{2\pi I}\left[\frac{\mu^2}{(r_{\rm ma}\,r_{\rm cor})^{3/2}}\right]$$

$$\boxed{\left|\dot{\nu}_{\rm sd}^{(0)}\right| < \left|\dot{\nu}_{\rm sd}^{(t)}\right| \ll \left|\dot{\nu}_{\rm sd}^{\rm obs}\right| < \left|\dot{\nu}_{\rm sd}^{(m)}\right|}$$

Ikhsanov, Likh & Beskrovnaya, Astronomy Reports, 58, 376 (2014) [arXiv:1402.1029]

Magnetic-Levitation Accretion onto a Neutron Star

1. Accretion from a magnetized wind $(\beta_0 \sim 1)$
2. Deceleration of the free-falling material at the Shvartsman radius $R_{\rm sh}$
3. Formation of the non-Keplerian Magnetically-Levitating Disk (MAGLEV Disk)
4. Diffusion of accreting material into the stellar MF at the magnetospheric boundary

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New parameters:

Shvartsman radius

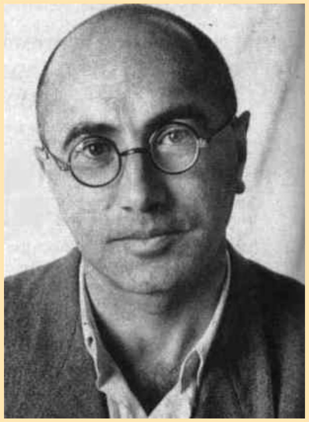
$$R_{\rm sh} = \beta_0^{-2/3} \left(\frac{c_{\rm s}(R_{\rm G})}{v_{\rm rel}} \right)^{4/3} R_{\rm G}$$

Magnetospheric radius

$$r_{\rm ma} = \left(\frac{c\, m_{\rm p}^2}{16\sqrt{2}\, e\, k_{\rm B}} \right)^{2/13} \frac{\alpha_{\rm B}^{2/13}\ \mu^{6/13}\ (GM_{\rm ns})^{5/13}}{T_0^{2/13}\ L_{\rm x}^{4/13}\ R_{\rm ns}^{4/13}}$$

ML-torque

$$K_{\rm ml} = k_{\rm m} \frac{\mu^2}{(r_{\rm ma}\ r_{\rm cor})^{3/2}} \left(1 - \frac{\Omega_{\rm ml}(r_{\rm ma})}{\Omega_{\rm s}} \right)$$



Yakov Zel'dovich

Final Remarks

Victory Shvartsman

A Farewell to Accreting Magnetars...

Welcome to Magnetic-Levitation Accretion

Gennady Bisnovatyi-Kogan

Alex Ruszmaikin