The magnetic field strength of neutron stars

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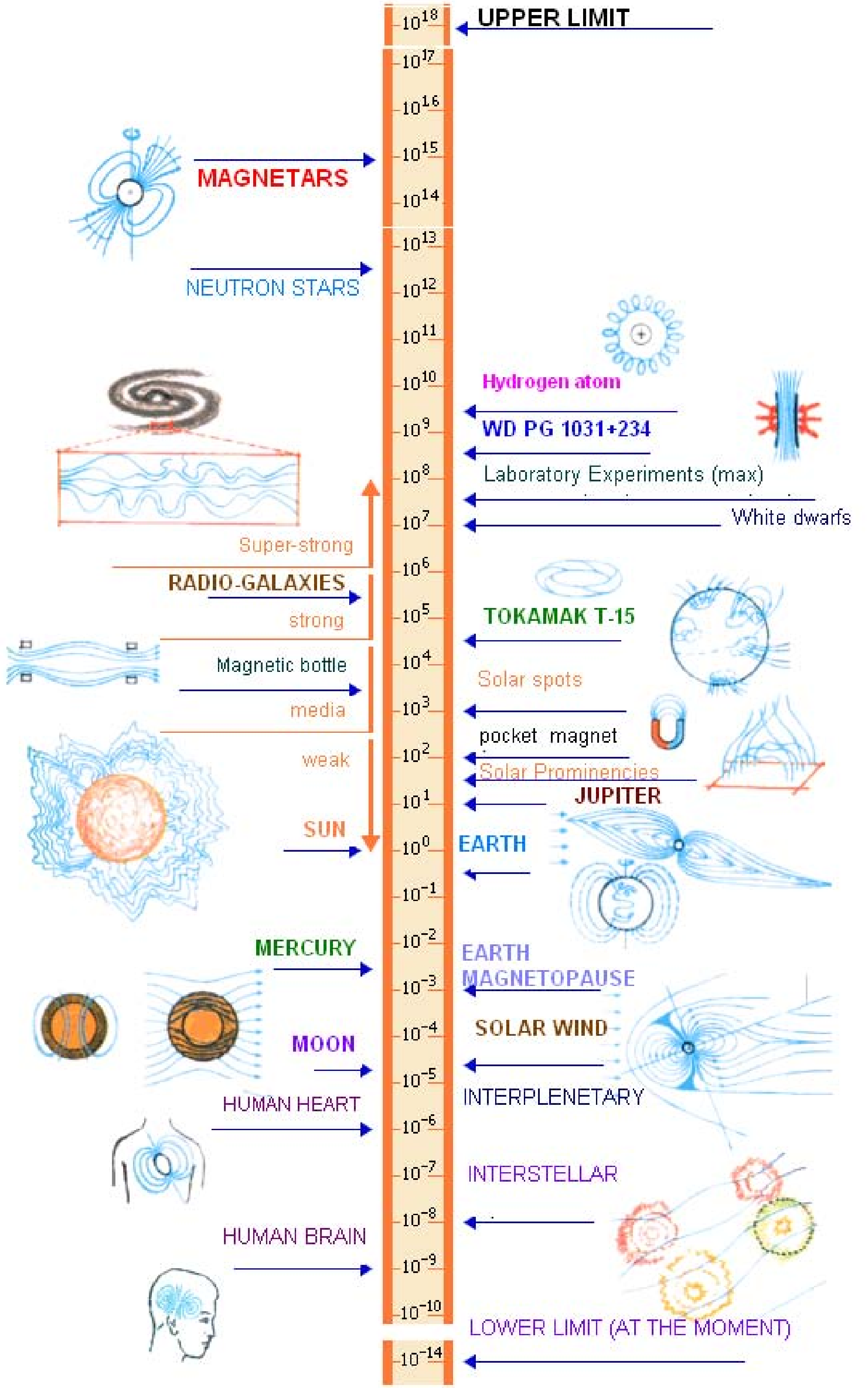
7. Ikhsanov N.R., Kim, V.Y., Beskrovnaya, N.G. & Pustil'nik, L.A. 2013 ApSS, **346**, 105



UPPER LIMIT

Gravitational Energy ≡ Magnetic energy

$$B_{\max} \sim 10^{18}\ \mathrm{G}$$

QUANTUM CRITICAL FILED

$$B_{\rm cr} = \frac{m_{\rm e}^2\, c^3}{e\, \hbar} \simeq 4.4\times 10^{13}\ \mathrm{G}$$

REGULAR FIELD OF NEUTRON STARS

Magnetic Flux Conservation during Collapse

$$B_{\rm ns} \sim B_{\rm in}\left(\frac{R_{\rm in}}{R_{\rm ns}}\right)^2 \simeq 10^{12}\ \mathrm{G}\ \times$$

$$\times \left(\frac{B_{\rm in}}{100\ \mathrm{G}}\right)\left(\frac{R_{\rm in}}{10^6\ \mathrm{km}}\right)^2\left(\frac{R_{\rm ns}}{10\ \mathrm{km}}\right)^{-2}$$

Magnetic Field Measurements

There are four ways of constraining the pulsars B field

- Measure the lowest cyclotron absorption line energy

$$B_{\rm CRSF} \leq 10^{12} \left(\frac{E_{\rm cyc}}{11.6\,{\rm keV}} \right) {\rm G}$$

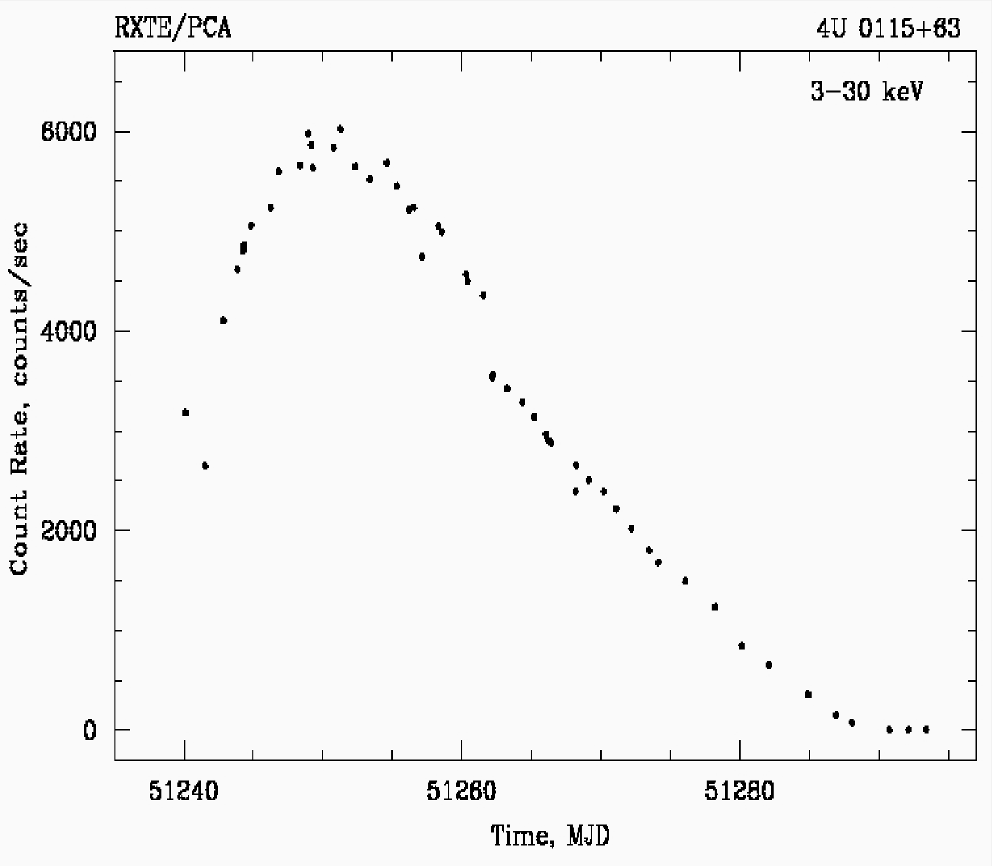
- Measure the spin-down rate of pulsars;

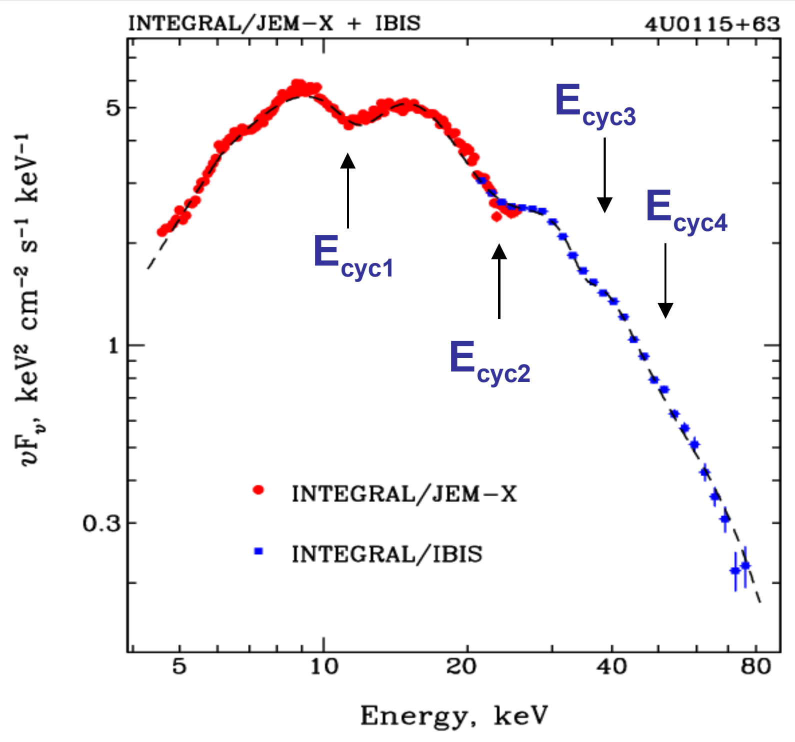
- Measure the spin-up rate at high luminosity of the accretion-powered X-ray pulsars;

- Observations of the cutoff of accretion due to centrifugal inhibition;

Вспышки излучения 4U 0115+63 1999 и 2004 гг.

Цыганков и др. (2007)





Максимальный диапазон светимостей ~1x10^{37} – ~2x10^{38} эрг/с (d~7 кпс)

Параметры спектра

α = 0.09+/-0.01

E_{cut} = 8.9+/-0.1 кэВ

E_{cyc1} = 11.16+/-0.03 кэВ

E_{cyc2} = 21.2+/-0.1 кэВ

E_{cyc3} = 34.6+/-0.2 кэВ

E_{cyc4} = 44.9+/-0.3 кэВ

$E_{cyc1}/E_{cyc2}/E_{cyc3}/E_{cyc4}$= 1/1.9/3.1/4.0

Зависимость доли пульсирующего излучения от светимости и энергетического диапазона

Временной анализ данных обсерватории ИНТЕГРАЛ/IBIS в узких энергетических каналах.
Только яркие источники (поток в 20-50 кэВ > ~100 mCrab):

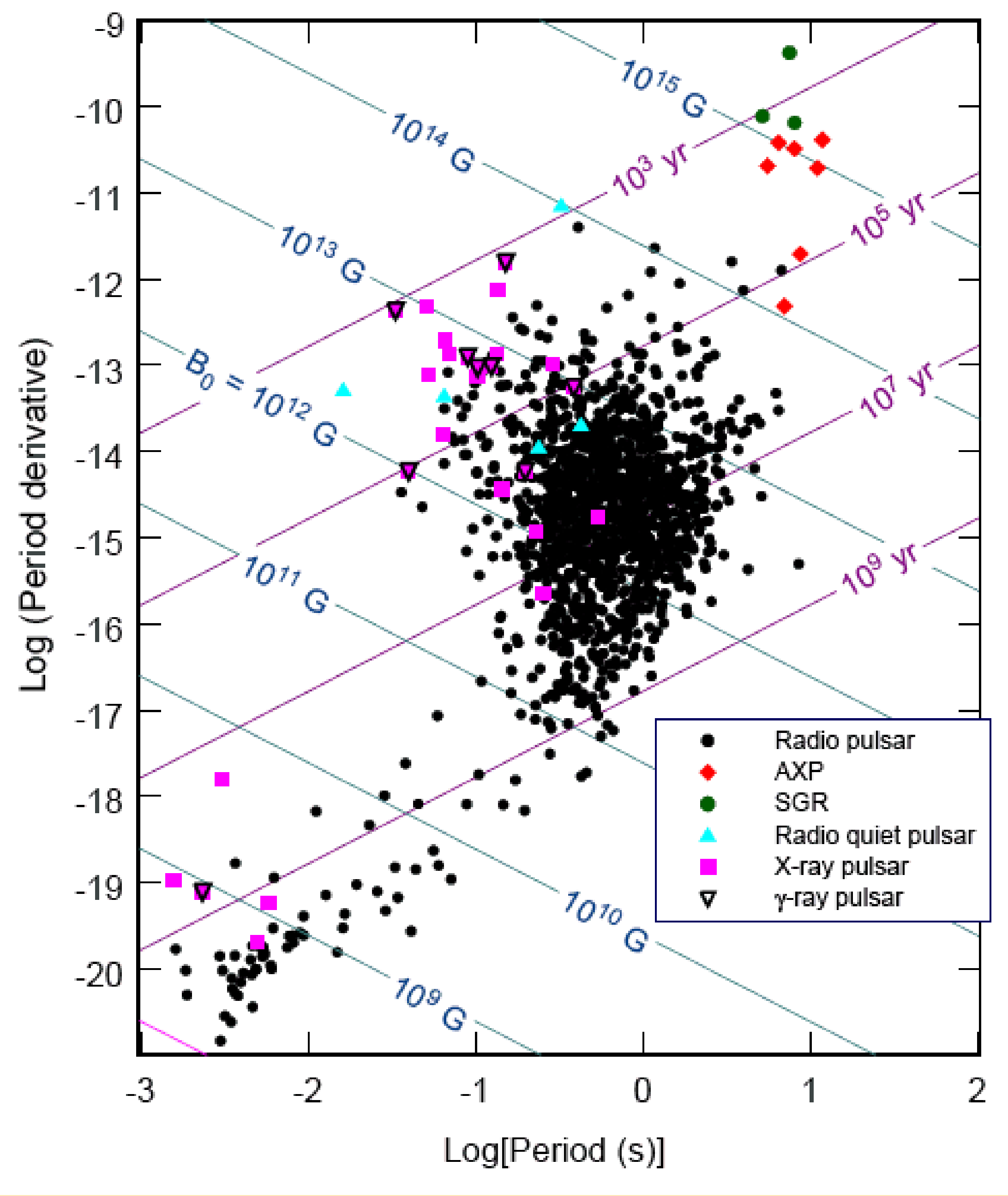
Источник	***Ecyc***
4U 0115+63	~11, 21, 34, 45 кэВ
V 0332+53	~28, 55 кэВ
A 0535+262	~45, 100 кэВ
Hercules X-1	~38 кэВ
Vela X-1	~22, 56 кэВ
GX 301-2	~50 кэВ
GX 1+4	-
Cen X-3	~31 кэВ
OAO 1657-415	~78 кэВ
EXO 2030+375	-

Cyclotron Line Measurements

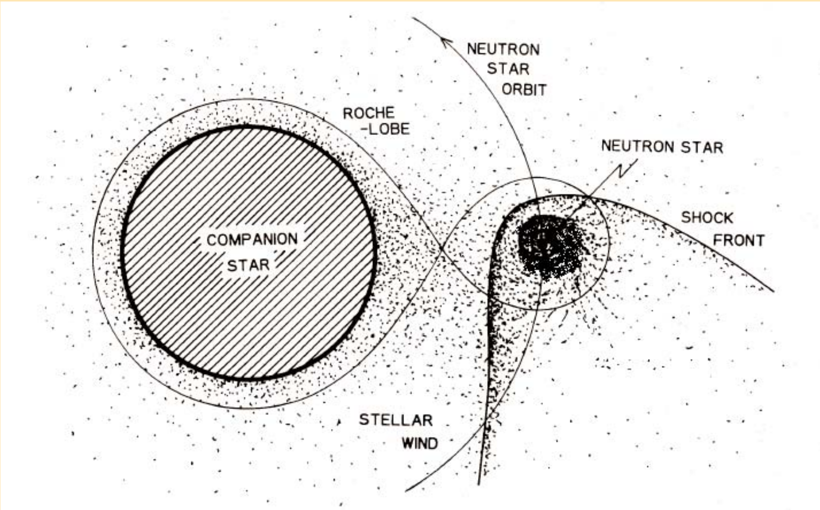
Class	Name	E_{cyc} (keV)	Reference
Be/X-ray	EXO 2030+375	10.5	Wilson et al. 2007
	4U 0115+63	11.5	White, Swank & Holt, 1983
	V 0332+53	28.5	Makishima et al., 1991
	X Per	28.6	Colburn et al., 2001
	Cep X-4	30.0	Mihara et al. 1991
	XTE J1946+274	34.9	Heindl et al. 2001
	MX 0656-072	36.0	McBride, V.A. et al., 2005
	A 0535+26	47.0	Caballero et al 2007
Disk Fed	Cen X-3	30.0	Burderi et al., 2000
	4U 1626-67	39.0	Coburn et al. 2000
	Her X-1	42.0	Manchanda, 2003
Wind Fed	4U 1907+09	18.3	Cusumano et al. 1998
	4U 1538-52	20.7	Robba et al. 2001
	2S 0114+65	22.0	Bonning et al. 2005
	Vela X-1	23.3	Kreykenbohm et al., 2002
	4U 2206+54	32.0	Blay et al., 2006
	GX 301-2	42.4	La Barbera et al. 2005

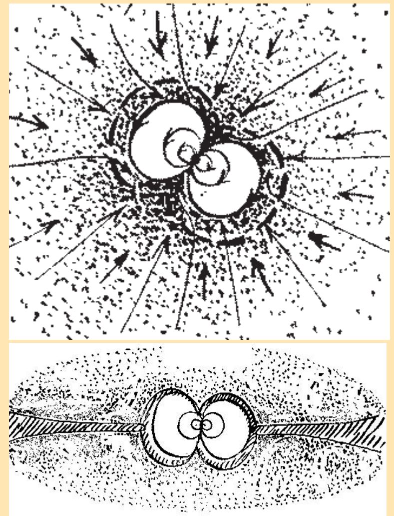
Magneto-dipole waves

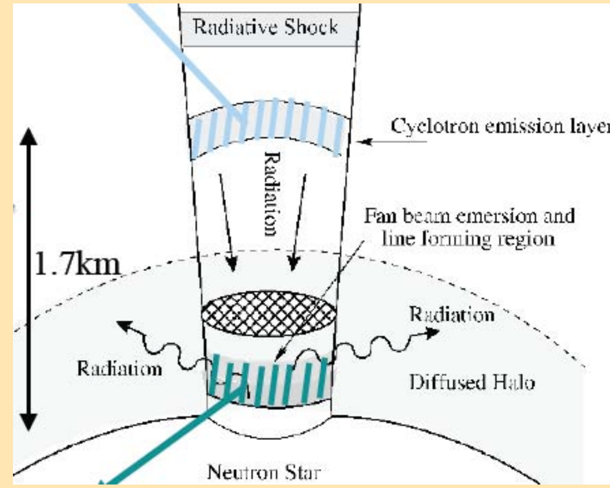
$$L_{\rm md} = f_{\rm m}\frac{\mu^2{\omega_{\rm s}}^4}{c^3} = I\omega\dot{\omega}$$



Accretion-powered pulsars in wind-fed HMXBs







MASS CAPTURE

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

Bondi radius $r_{\rm G} = \dfrac{2GM_{\rm ns}}{V_{\rm rel}^2}$

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

MASS ACCRETION

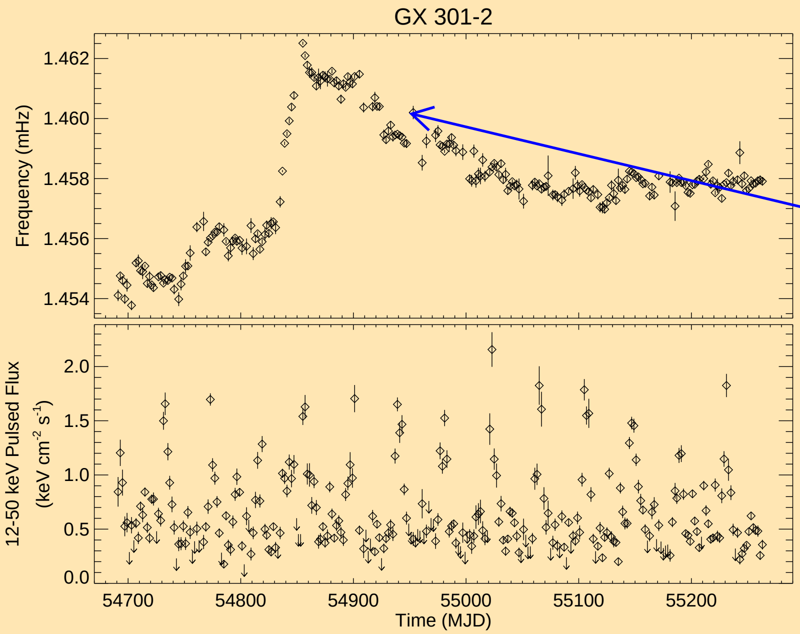
Mass accretion rate $\dot{\mathfrak{M}}_{\rm a} = \dfrac{L_{\rm x} R_{\rm ns}}{G M_{\rm ns}}$

Magnetic field $B_{\rm CRSF} \leq 10^{12} \left(\dfrac{E_{\rm cyc}}{11.6\,{\rm keV}}\right)$ G

Dipole magnetic moment $\mu \simeq \dfrac{1}{2}\, B_{\rm CRSF}\, R_{\rm ns}^3$

- **Accretion of mass**
- **Accretion of angular momentum**

Spin Evolution (Spin-up $\longleftrightarrow$ Spin-down) $\quad \nu = 1/P_{\rm s}$



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

$$|K_{\rm sd}| \geq 2\pi \, I \, |\dot{\nu}_{\rm sd}|$$

$$|K_{\rm sd}(r_{\rm A})| \leq \begin{cases} |K_{\rm sd}{}^{(0)}| = \mu^2/r_{\rm cor}^3 \\ |K_{\rm sd}{}^{(\rm t)}| = \dot{\mathfrak{M}} \, \omega_{\rm s} \, r_{\rm A}^2 \end{cases}$$

Name	B_{12}, G	$P_{\rm s}$, s	$\left\lvert \dot{\nu}_{\rm sd}^{\rm obs} \right\rvert$	$\left\lvert \dot{\nu}_{\rm sd}^{(0)} \right\rvert$	$\left\lvert \dot{\nu}_{\rm sd}^{(t)} \right\rvert$
OAO 1657-415	3.2	38	3.2	0.056	0.18
Vela X-1	2.6	283	0.2	0.0003	0.012
4U 1907+09	2.1	438	0.04	0.0002	0.008
4U 1538-522	1.8	529	0.06	0.0002	0.008
GX 301-2	4.0	683	0.1	0.003	0.02

The Problem (since 1973)

The **spin-down torque** applied to Long-Period X-ray Pulsars in HMXBs

is a factor of 10 larger

than the **maximum possible spin-down torque** expected within

the **conventional scenario** of accretion from a **non-magnetized stellar wind**.

Conventional scenario:

- Magnetospheric radius: $r_{\rm m} \equiv r_{\rm A} = \left(\dfrac{\mu^2}{\dot{\mathfrak{M}} \sqrt{G M_{\rm ns}}} \right)^{2/7}$; $\left[\dot{\mathfrak{M}} = \dfrac{L_{\rm X} R_{\rm ns}}{G M_{\rm ns}} \right]$

- Spin-down torque: $$|K_{\rm sd}(r_{\rm A})| \sim \begin{cases} |{K_{\rm sd}}^{(0)}| = \mu^2 \times \left[\dfrac{4\pi^2\ k_{\rm t}}{G M_{\rm ns}\ P_{\rm s}^2} \right] \\ |{K_{\rm sd}}^{(\rm t)}| = \mu^{8/7} \times \left[\dfrac{2\pi\ k_{\rm t}\ L_{\rm X}^{3/7} R_{\rm ns}^{3/7}}{(G M_{\rm ns})^{5/7}\ P_{\rm s}} \right] \end{cases}$$

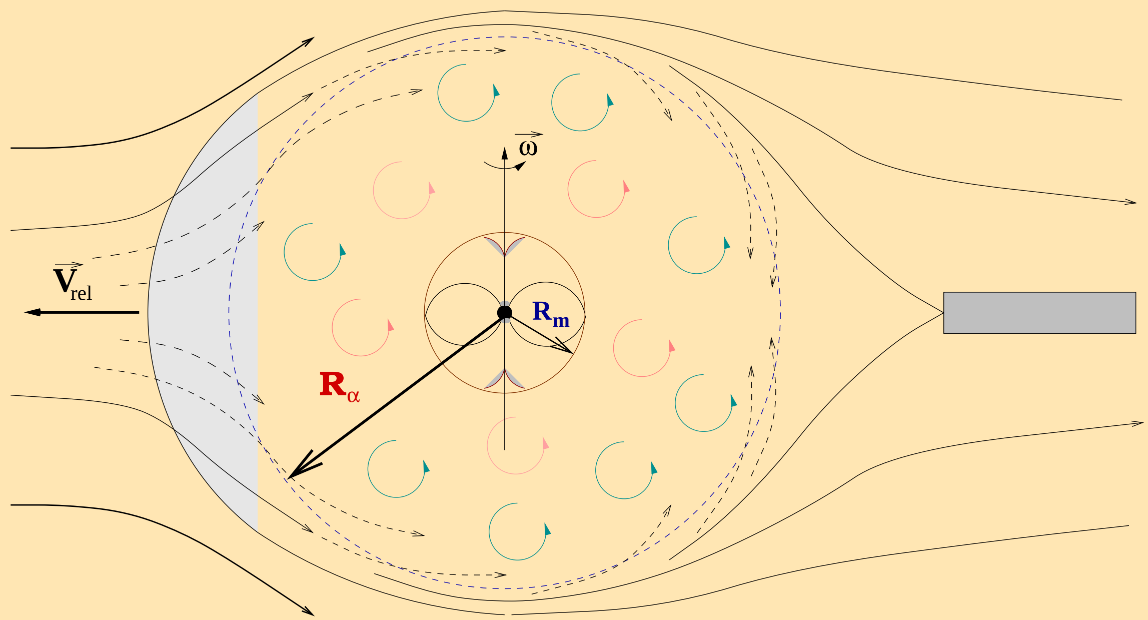
Torque definition

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

Model task:

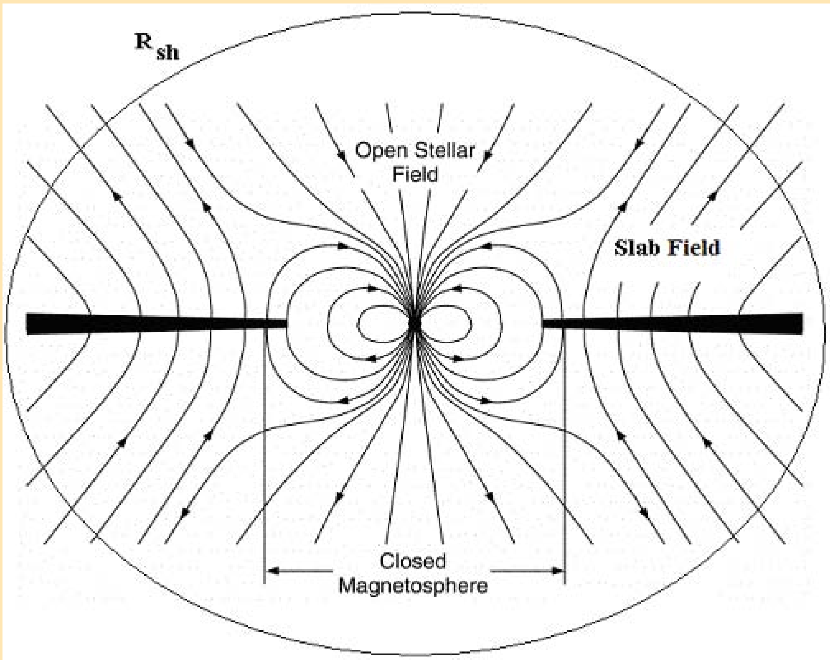
A sphere of the radius r_{m}

is rotating in a viscose medium



Spin-down torque in general case (I of II steps)

$$|K_{\rm sd}(r_{\rm m})| \; = \; \nu_{\rm t}\, S_{\rm eff}(r_{\rm m})\, \rho(r_{\rm m})\, v_\phi(r_{\rm m})$$



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

Effective Area $S_{\rm eff} = 2\pi r_{\rm m}\, h_{\rm s}(r_{\rm m})$

Thickness $h_{\rm s}(r_{\rm m}) = c_{\rm s}^2(r_{\rm m}) \left(\frac{r_{\rm m}^2}{GM_{\rm ns}}\right)$

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

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

$$|K_{\rm sd}(r_{\rm m})| \; = \; [\, k_{\rm t}\, \ell_{\rm t}\, v_{\rm t}\,] \left[\frac{\mu^2}{r_{\rm m}^2}\, \frac{\omega_{\rm s}}{GM_{\rm ns}}\right] \left(1 - \frac{\Omega(r_{\rm m})}{\omega_{\rm s}}\right)$$

Spin-down torque in general case (II of II steps)

$$|K_{\rm sd}(r_{\rm m})| \;=\; [\,k_{\rm t}\;\ell_{\rm t}\;v_{\rm t}\,]\;\left[\frac{\mu^2}{r_{\rm m}^2}\,\frac{\omega_{\rm s}}{GM_{\rm ns}}\right]\;\left(1-\frac{\Omega(r_{\rm m})}{\omega_{\rm s}}\right)$$

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

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

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

$$|K_{\rm sd}(r_{\rm m})| \;=\; \left[k_{\rm t}\;r_{\rm m}\left(\frac{GM_{\rm ns}}{r_{\rm m}}\right)^{1/2}\right]\;\left[\frac{\mu^2}{r_{\rm m}^2}\,\frac{\omega_{\rm s}}{GM_{\rm ns}}\right]\;\left(1-\frac{\Omega(r_{\rm m})}{\omega_{\rm s}}\right)$$

$$=\; k_{\rm t}\,\frac{\mu^2}{r_{\rm m}^{3/2}}\;\left[\frac{\omega_{\rm s}}{(GM_{\rm ns})^{1/2}}\right]\;\left(1-\frac{\Omega(r_{\rm m})}{\omega_{\rm s}}\right)$$

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

Ikhsanov N.R. & Beskrovnaya, N.G. 2012 Astronomy Reports, **56**, 589

Ikhsanov N.R. & Finger, M.H. 2012 Astrophysical Journal, **753**, 1

Correspondence principle is satisfied

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

I. Accretion from a Turbulent-dominated Atmosphere

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

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

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

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

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

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

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

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

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

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

Evaluation of the Magnetospheric Radius from Spin Evolution

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

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

Name	B_{12}, G	$P_{\rm s}$, s	$\|\dot{\nu}_{\rm sd}\|$, 10^{-12} Hz/s	$r_{\rm m}$, 10^8 cm	$r_{\rm A}$, 10^8 cm	$r_{\rm m}/r_{\rm A}$
OAO 1657-415	3.2	38	3.2	1.4	6.8	0.2
Vela X-1	2.6	283	0.3	1.5	8.3	0.18
4U 1907+09	2.1	438	0.04	2.9	6	0.48
GX 301-2	4	683	0.1	1.9	5.5	0.34
X Persei	3.3	837	0.024	4.5	23	0.2

Constrains on Accretion Scenario in LPXPs

Basic criteria:

- Slowly rotating accretion flow $\Omega(r_{\rm m}) < \omega_{\rm s}$
- Small magnetospheric radius $r_{\rm m} \ll r_{\rm A}$

I. Keplerian disk can be excluded $P_{\rm eq} \sim 4 - 10\,{\rm s} \ll P_{\rm obs}$

II. Quasi-spherical accretion can also be excluded $r_{\rm m}^{\rm (sp)} \geq r_{\rm A}$

III. Magnetic accretion

- **Accretion from a magnetized wind**
- **Formation of a non-Keplerian magnetized disk-like envelope (magnetic slab)**

Some Historical Points of Magnetic Accretion Scenario

1959	Star formation in a magnetized medium	Mestel, L. 1959, MNRAS, 119, 223
1964 – 1965	Magnetic Collapse	Kardashev, N.S. 1965, Sov. Astron., 8, 643
1969	Fossil magnetic field in spherical flow onto a Neutron Star	Bisnovatyi-Kogan, G.S. Fridman, A.M. 1969, Sov. Astron. 13, 566
1971	Magnetic control of accretion onto a black hole flow deceleration at $R_{\rm sh}$	Shvartsman, V.F. 1971, SvA, 15, 377
1974 – 1976	Non-Keplerian magnetic disk around a black hole	Bisnovatyi-Kogan, G.S., Ruzmaikin, A.A. 1974, ApSS, 28, 45 Bisnovatyi-Kogan, G.S., Ruzmaikin, A.A. 1976, ApSS, 42, 401
2003 – 2006	Non-Keplerian magnetic disk simulations for a Black Hole (magnetically arrested disk)	Igumenshchev, I.V., Narayan, R., Abramowicz, M.A. 2003, ApJ, 592, 1042 Igumenshchev, I.V. 2006, ApJ, 649, 361
2012 – 2013	Non-Keplerian magnetic disk around a Neutron Star (magnetic slab)	This talk (+ 7 papers by Ikhsanov, N.R. et al.)

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

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

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

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

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

Shvartsman radius

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

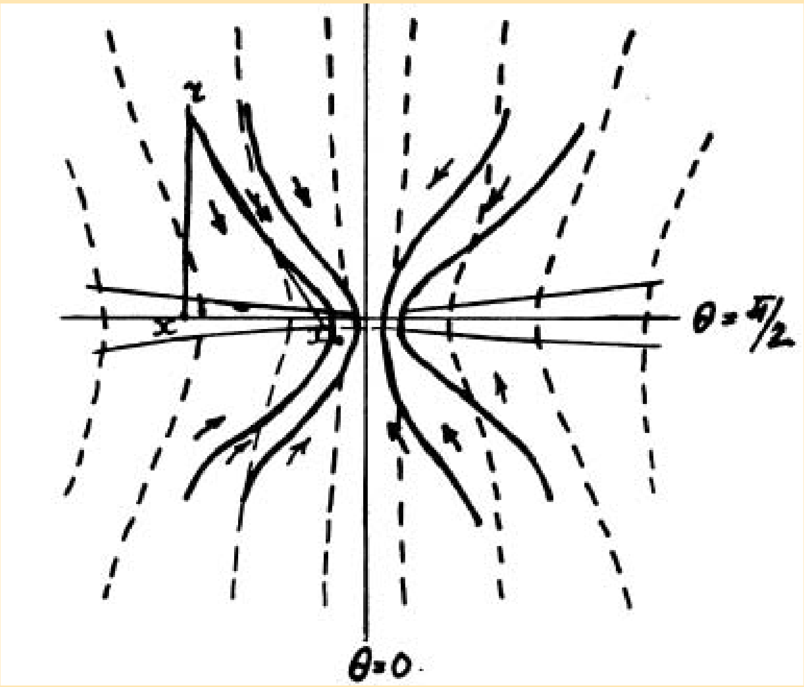
$$R_{\rm sh} = \beta^{-2/3} \left(\frac{c_{\rm s}}{v_{\rm rel}}\right)^{4/3} R_{\rm G}$$

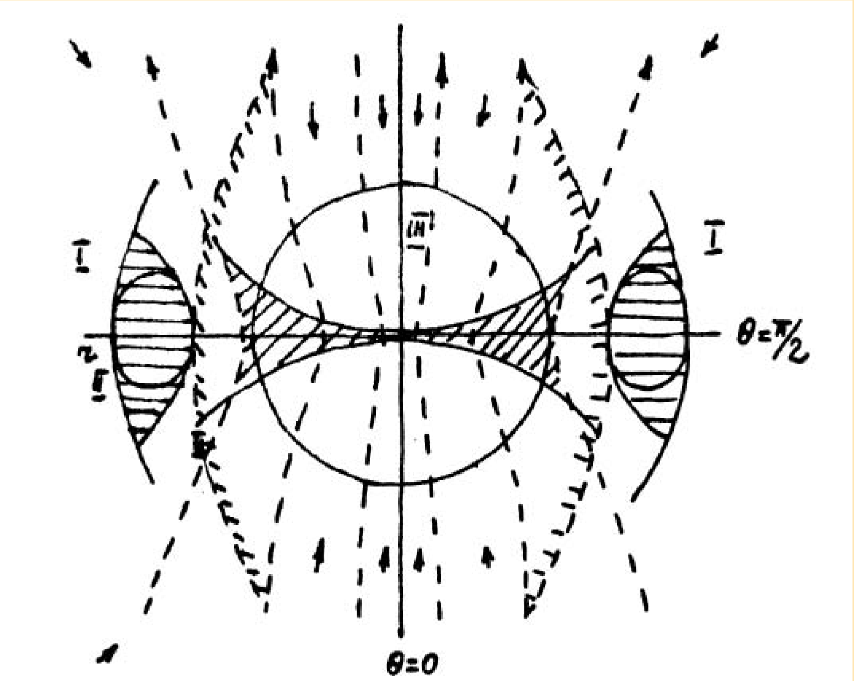
Shvartsman, V.F. 1971, Soviet Astronomy, **15**, 377

Non-Keplerian Magnetic Slab

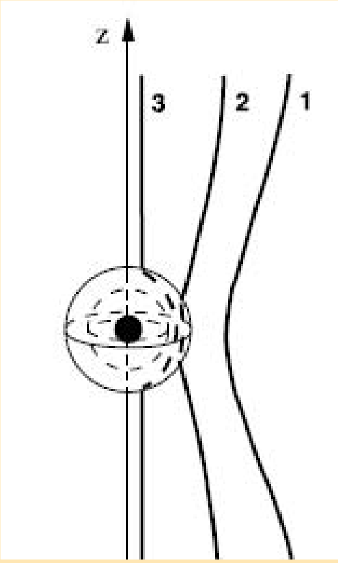
$$t_{\rm rec} = \frac{r}{\eta_{\rm m}\ v_{\rm A}} = \eta_{\rm m}^{-1}\ t_{\rm ff}\ \left(\frac{v_{\rm ff}}{v_{\rm A}}\right)$$

Bisnovatyi-Kogan & Ruzmaikin 1974, ApSS, 28, 45; 1976, ApSS, 42, 401

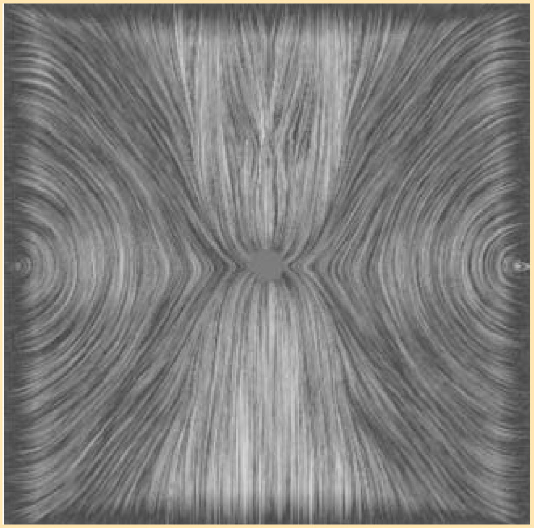




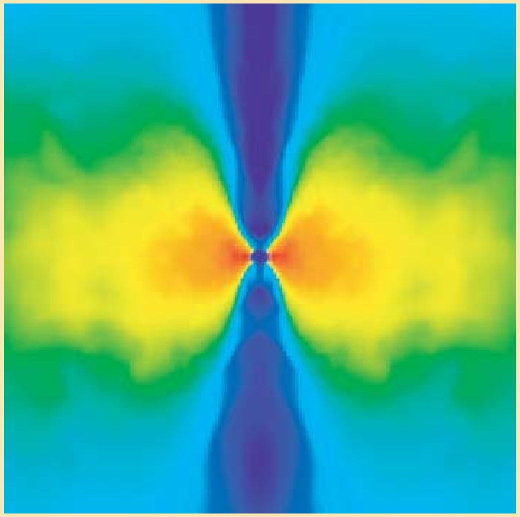
Igumenschev, Narayan & Abramowicz 2003, ApJ, 592, 1042



Magnetic field



Density



Magnetic accretion in X-ray pulsars

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

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

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

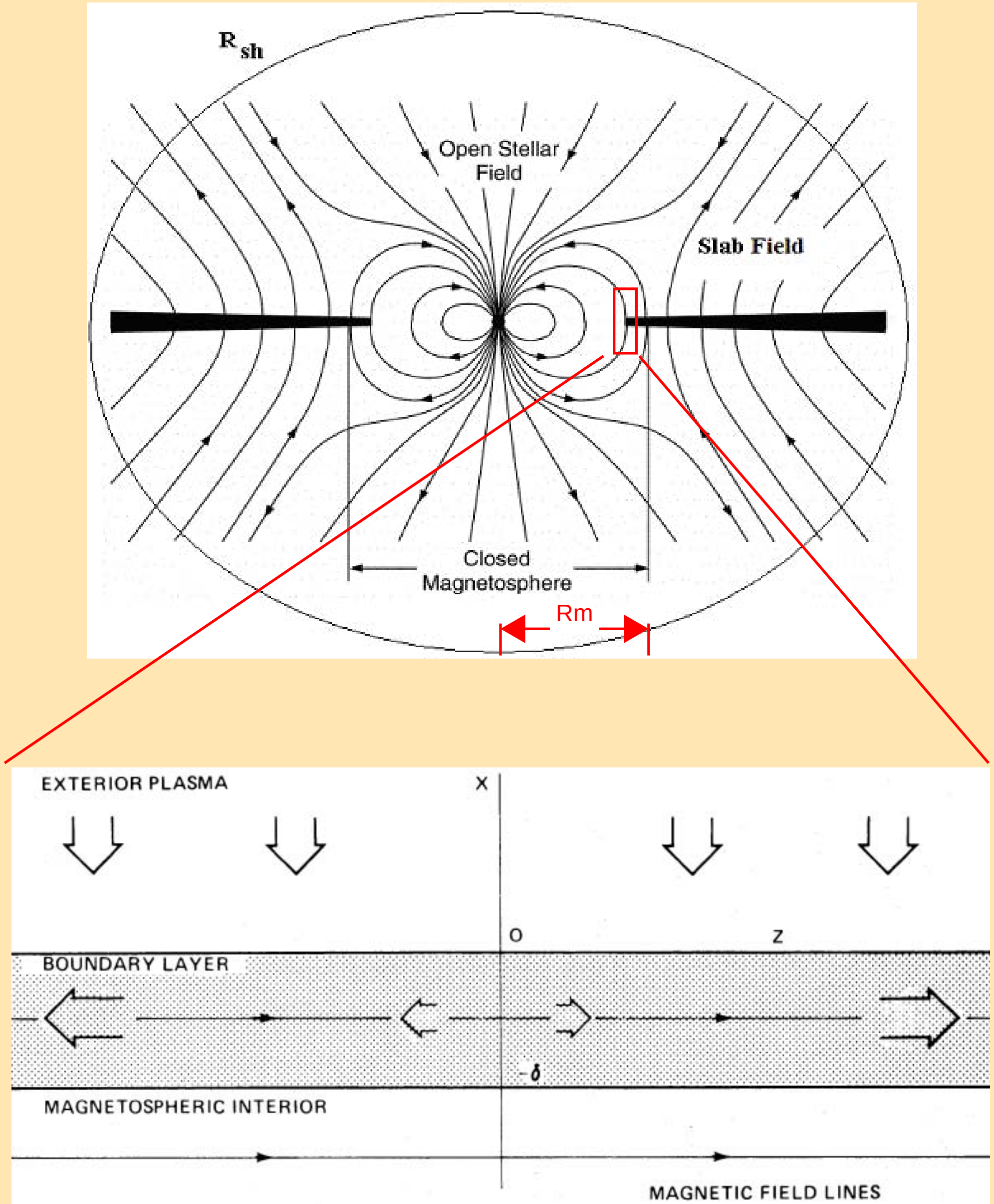
Three possible accretion scenarios

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

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

Magnetic slab $\longleftarrow$ $v_{\rm cr} < v_{\rm rel} < v_{\rm ma}$

Magnetic accretion onto a magnetized neutron star



$$c_{\mathrm{s}}(r_{\mathrm{m}}) \;>\; v_{\phi}(r_{\mathrm{m}})$$

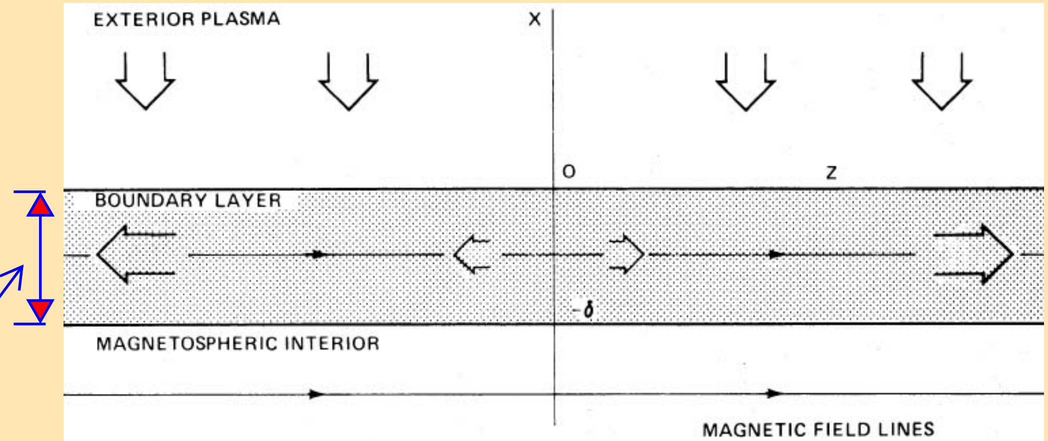
$$v_{\phi}(r_{\mathrm{m}}) \;\ll\; v_{\mathrm{k}}(r_{\mathrm{m}})$$

$$v_{\mathrm{A}}(r_{\mathrm{m}}) \;\sim\; c_{\mathrm{s}}(r_{\mathrm{m}})$$

$$r_{\mathrm{ma}} \;\leq\; r_{\mathrm{m}} \;\leq\; r_{\mathrm{A}}$$

Magnetospheric radius of a neutron star which accretes material from the non-Keplerian magnetic slab

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



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

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

Ikhsanov N.R. & Beskrovnaya, N.G. 2012 Astronomy Reports, **56**, 589

Ikhsanov N.R., Kim, V.Y., Beskrovnaya, N.G. & Pustil'nik, L.A. 2013 Astrophysics & Space Sci., first on-line

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

Name	B_{12}, G	$P_{\rm s}$, s	$\left\|\dot{\nu}_{\rm sd}^{\rm obs}\right\|$	$\left\|\dot{\nu}_{\rm sd}^{(0)}\right\|$	$\left\|\dot{\nu}_{\rm sd}^{(t)}\right\|$	$\left\|\dot{\nu}_{\rm sd}^{(m)}\right\|$
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

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

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

Magnetic Accretion onto a Neutron Star

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 $\dot{\mathfrak{M}}_{\rm diff}(r_{\rm m}) \;=\; L_{\rm X} R_{\rm ns}/G M_{\rm ns}$

New parameters:

Shvartsman radius

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

Magnetospheric radius

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

Spin-down torque

$$|\,K_{\rm sd}\,| \;=\; k_{\rm m}\,\frac{\mu^2}{(r_{\rm ma}\;r_{\rm cor})^{3/2}}\left(1 - \frac{\Omega_{\rm sl}(r_{\rm ma})}{\omega_{\rm s}}\right)$$

Accretion-powered Be/X-ray Pulsar SXP 1062

Name	P_s, s	$\log L_x$	E_{cyc}	$\dot{\nu}$, Hz/s	P_{orb}, d	Sp. type	d
SXP 1062	1070	35.8	–	-2.6×10^{-12}	656	B0 IIIe	60 kpc

Magnetic field determination

(Ikhsanov N.R. 2012, MNRAS, **424**, L39)

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

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

Spin Evolution of SXP 1062 (Ikhsanov N.R. 2012, MNRAS, **424**, L39)

Name	P_s, s	$\log L_x$	B_*	$\dot{\nu}$, Hz/s	P_{orb}, d	Sp. type	d
SXP 1070	1062	35.8	4×10^{13} G	-2.6×10^{-12}	656	B0 IIIe	60 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	$\tau_{prop} \sim \frac{\pi I r_{ma}^3}{\mu^2 P_{ej}}$	$\tau_{prop} \sim 110$ yr
Accretor phase	$\tau_{acc} \sim \frac{1}{2 \mid \dot{\nu}_{obs} \mid P_{prop}}$	$\tau_{acc} \sim 600$ yr

Age of the Pulsar is $\tau \sim (1-2) \times 10^4$ yr

Young Isolated X-ray Pulsar 1E 161348-5055

Name	$P_{\rm s}$, s	$L_{\rm x}$, erg/s	$E_{\rm cyc}$	$\lvert\dot{\nu}\rvert$, Hz/s	Type	d, kpc
1E 1613	24030	10^{34}	–	3×10^{-18}	Isolated	3.3

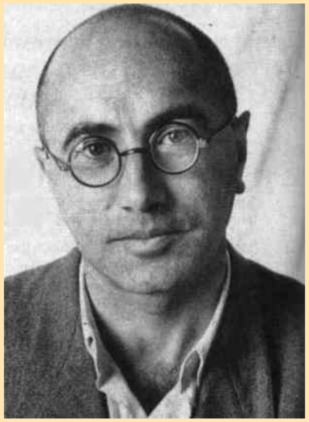
Magnetic field determination (Ikhsanov N.R., et al. 2013, ApSS, **346**, 105)

Spin-down scenario	Magnetic field	Magnetospheric radius
Ejector (spin-powered pulsar)	$B_* \geq 4 \times 10^{18}$ G	$r_{\rm A} > 100\, r_{\rm cor}$
Keplerian fossil disk	$B_* \geq 10^{16}$ G	$r_{\rm A} > 2.5\, r_{\rm cor}$
Magnetic fossil slab	$B_* \geq 8 \times 10^{11}$ G	$r_{\rm ma} \sim 0.002\, r_{\rm cor}$

$$B \geq 10^{12}\,{\rm G} \left(\frac{\tau}{2000\,{\rm yr}}\right)^{-13/17} \times k_{\rm m}^{-13/17}\,\alpha_{\rm B}^{3/17}\,I_{45}^{13/17}\,m^{8/17}\,T_6^{3/17}\,\mathfrak{M}_{14}^{-6/17}$$

Магнитная реверсная аккреция: параметры источников

Название	$P_{\rm s}$, с	$\|\dot{\nu}_{\rm sd}\|$, 10^{-12} Гц с$^{-1}$	$L_{\rm X}$, 10^{34} эрг с$^{-1}$	B_*, 10^{12} Гс	$r_{\rm cor}$, 10^8 см	$r_{\rm ma}$, 10^8 см	$a_{\rm p}$, 10^5 см	$T_{\rm bb}$, кэВ
SGR 1627-41	2.6	2.8	0.25	3.9	3.2	1.2	0.9	0.5
SGR 1900+14	5.2	3.4	9.0	2.7	5.2	1.0	1.0	1.1
SGR 1806-20	7.6	13	16	12	6.6	1.7	0.8	1.4
SGR 0526-66	8.05	0.59	14	1.2	6.9	0.6	1.3	1.1
1E 1547.0-5408	2.07	11	0.08	0.63	2.8	2.1	0.7	0.4
CXOU J174505.7-381031	3.83	4.4	6.0	2.3	4.2	1.0	1.0	0.98
PSR J1622-4950	4.33	0.9	0.063	1.5	4.6	1.2	0.9	0.33
XTE J1810-197	5.54	0.26	3.9	0.3	5.4	0.46	1.5	0.73
1E 1048.1-5937	6.45	0.55	0.6	0.31	5.95	0.83	1.1	0.53
1E 2259+586	6.98	0.01	2.2	0.024	6.3	0.17	2.4	0.49
CXOU J010043.1-721134	8.02	0.29	6.1	0.51	6.9	0.51	1.4	0.83
4U 0142+61	8.69	0.03	11	0.11	7.26	0.21	2.2	0.77
CXO J164710.2-455216	10.61	0.006	0.3	0.011	8.3	0.22	2.1	0.32
1RXS J170849.0-400910	11.0	0.16	5.9	0.4	8.5	0.46	1.5	0.81
1E J1841-045	11.8	0.28	19	0.99	8.9	0.49	1.4	1.1



Yakov Zel'dovich

Victory Shvartsman

Final Remarks

A Farewell to Magnetars...

Welcome to Magnetic Accretion

Gennady Bisnovatyi-Kogan

Alex Ruszmaikin