A new look at the Anomalous X-ray Pulsars (AXPs)

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Basic Properties of AXPs and SGRs

- **ISOLATED X-ray pulsars (several in SNRs);**
- **REGULAR spin-down at** $\dot{\nu} \sim 10^{-11} - 10^{-14}\,\mathrm{Hz\,s^{-1}}$;
- **X-ray luminosity EXCEEDS the spin-down power** $\left(L_\mathrm{X} > L_\mathrm{sd} = I_\mathrm{ns}\,\Omega\,\dot{\Omega}\right)$;
- **X-ray spectrum is SOFT** $\left(\,kT \sim 0.4 - 1\,\mathrm{keV}\,\right)$;
- **CLASTERING of spin periods around** $2 - 20\,\mathrm{s}$;
- **Bursting activity in soft gamma-rays** $\left(\,L_\gamma \gg L_\mathrm{Edd}\,\right)$.

Approaches to explain AXP phenomenon

- **An unusual Neutron Star (NS) in an ordinary environment**
  - Nuclear power (Bisnovatyi-Kogan & Chechetkin 1974);
  - Magnetic power "Magnetar" (Duncan & Thompson 1992);

- **An ordinary NS in an unusual environment**
  - A Low-Mass X-ray Binary powered by accretion (Mereghetti & Stella 1995);
  - An isolated NS accreting from a fossil disk (van Paradijs et al. 1995);

- **An unusual NS in an unusual environment**
  - Nuclear power + Magnetic power + Accretion power.

What powers the X-rays?

THE ASTROPHYSICAL JOURNAL, 442: L17–L20, 1995 March 20

THE VERY LOW MASS X-RAY BINARY PULSARS: A NEW CLASS OF SOURCES?

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ABSTRACT

While the distribution of spin periods of high-mass X-ray binaries spans more than four orders of magnitude (69 ms–25 minutes) the few known X-ray pulsars accreting from very low mass companions ($<1\ M_\odot$) have very similar periods between 5.4 and 8.7 s. These pulsars also display several other similarities, and we propose that they are members of a subclass of low-mass X-ray binaries (LMXBs) with similar magnetic field (a few times 10^{11} G), companion stars and, possibly, evolutionary histories. If they are rotating at, or close to, the equilibrium period, their properties are consistent with luminosities of the order of a few times 10^{35} ergs s^{-1}. These pulsars might represent the closest members of a subclass of LMXBs characterized by lower luminosities, higher magnetic fields, and smaller ages than nonpulsating LMXBs.

Astron. Astrophys. 299, L41–L44 (1995)

On the nature of the 'anomalous' 6-s X-ray pulsars

J. van Paradijs [1,2], R.E. Taam [3], and E.P.J. van den Heuvel [1]

Abstract. Recently it has become clear that there is a group of X-ray pulsars, with pulse periods close to 6 seconds which are distinct from accreting strongly magnetized neutron stars in X-ray binary systems. Here we argue that these objects are the recent products of the evolution of massive stars. They are unlikely to be neutron stars that formed through accretion induced collapse of a white dwarf. We propose that they are single neutron stars accreting from a disk, the recent remnants of the common-envelope evolution of a high-mass X-ray binary.

State by 1995

- AXPs in X-rays resemble Accretion-powered Pulsars;

- The accreting material comes from
  - a low mass companion star, or
  - a fossil Keplerian disk

- AXPs rotate at the equilibrium period

Magnetars, magnetars and only magnetars!

NATURE | VOL 393 | 21 MAY 1998

An X-ray pulsar with a superstrong magnetic field in the soft γ-ray repeater SGR1806 − 20

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Here we report the discovery of pulsations in the persistent X-ray flux of SGR1806 − 20, with a period of 7.47 s and a spindown rate of 2.6×10^{-3} s yr^{-1}. We argue that the spindown is due to magnetic dipole emission and find that the pulsar age and (dipolar) magnetic field strength are ~1,500 years and 8×10^{14} gauss, respectively. Our observations demonstrate the existence of 'magnetars', neutron stars with magnetic fields about 100 times stronger than those of radio pulsars,

Spin-down to the period of 7.47 s on a timescale of only 1,500 years!

Regularly spinning-down like a radiopulsar

$$\left(P_{\rm eq} \gg P_{\rm s}\right)$$

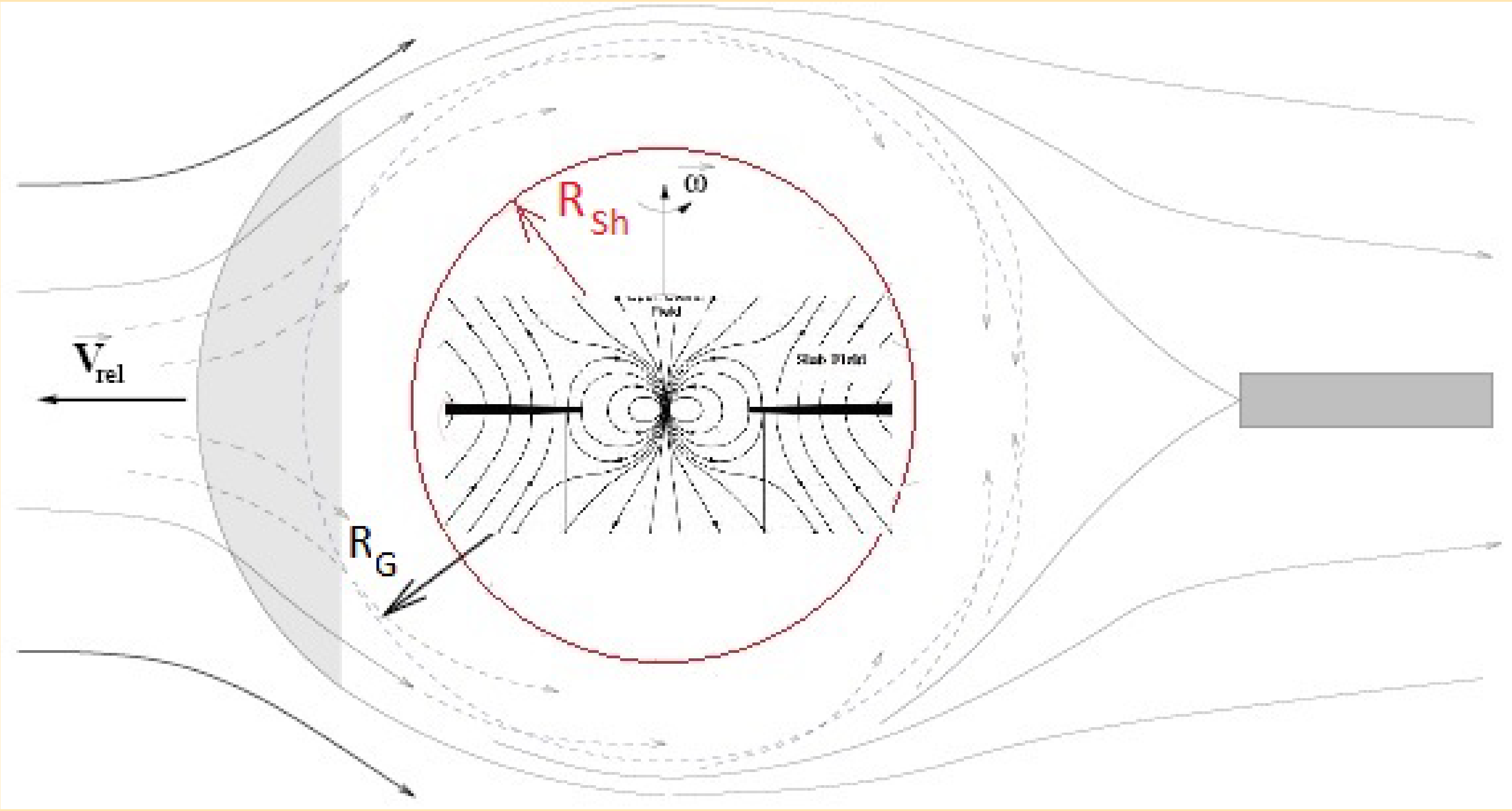
The spin-down torque inferred from observations is larger than the maximum possible torque expected in accretion scenarios

But why do AXPs resemble Accretion-powered Pulsars?

Accretion scenarios

- Quasi-spherical Accretion (a lack of a donor)
- Accretion from a fossil Keplerian Disk (at the equilibrium period)
- Magnetic-Levitation Accretion (What is this?)

Wind-fed accretion from a magnetized gas



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

Spherical accretion of a magnetized flow inside Bondi radius

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

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

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

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

$\beta_0 = \mathcal{E}_{\rm th}(R_{\rm G})/\mathcal{E}_{\rm m}(R_{\rm G})$

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

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

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

Shvartsman radius

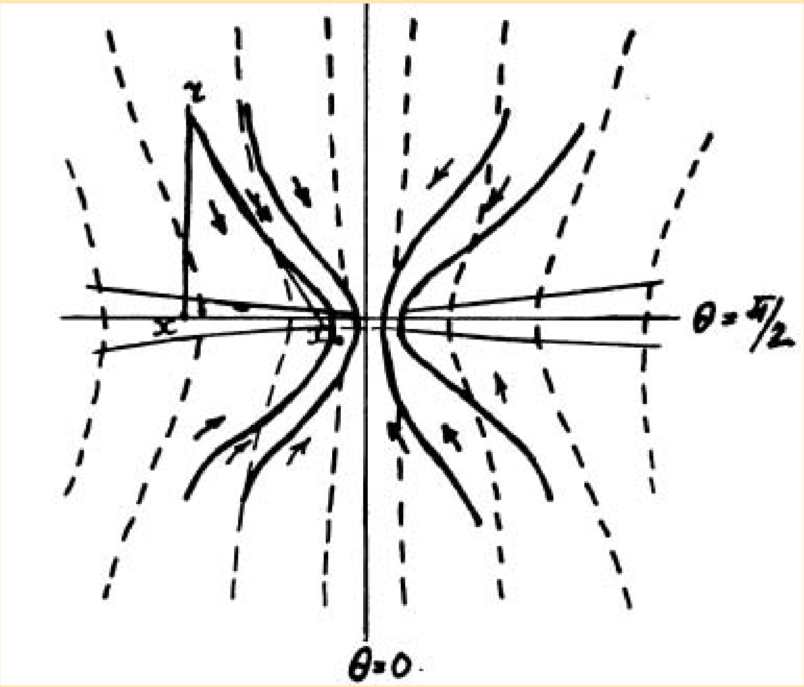
$$\mathcal{E}_{\rm m}(R_{\rm sh}) = \mathcal{E}_{\rm ram}(R_{\rm sh})$$

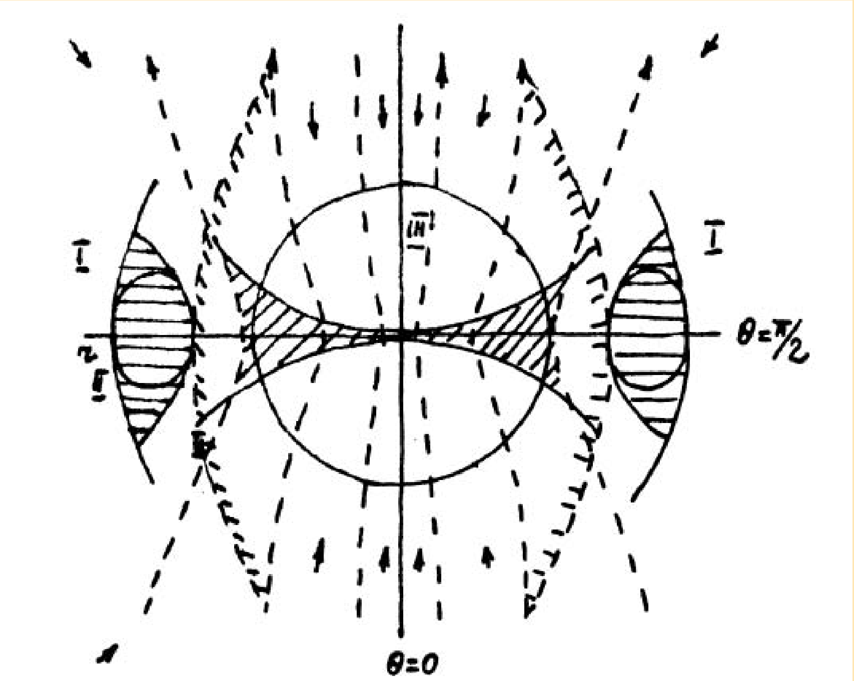
$$R_{\rm sh} = \beta_0^{-2/3} \left(\frac{c_{\rm s}(R_{\rm G})}{v_{\rm rel}}\right)^{4/3} R_{\rm G}$$

Non-Keplerian Magnetically-Levitating Disk

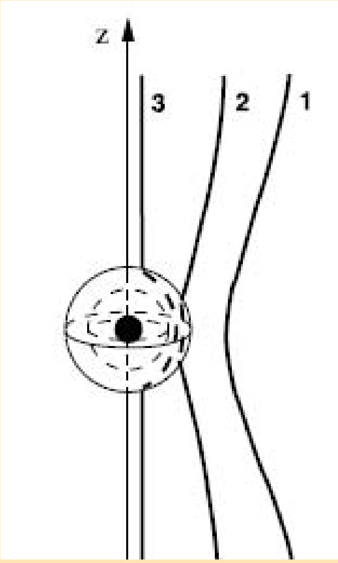
$$t_{\rm rec} = \frac{r}{\eta_{\rm m}\ v_{\rm A}} = \eta_{\rm m}^{-1}\ t_{\rm ff}\ \left(\frac{v_{\rm ff}}{v_{\rm A}}\right)$$

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

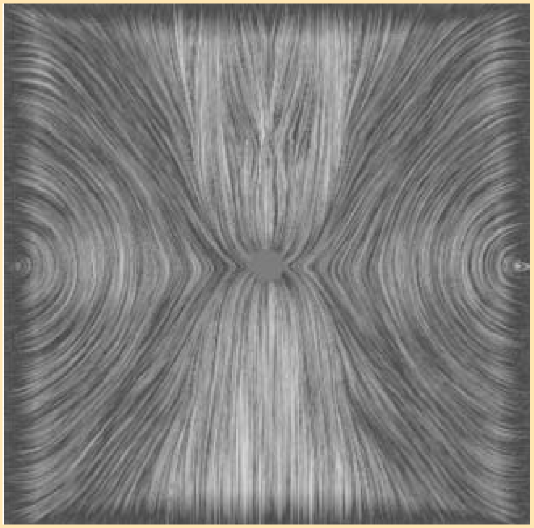




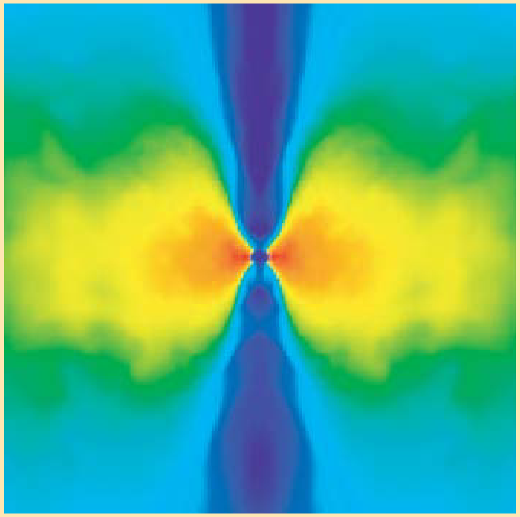
Igumenschev, Narayan & Abramowicz 2003, ApJ, 592, 1042



Magnetic field



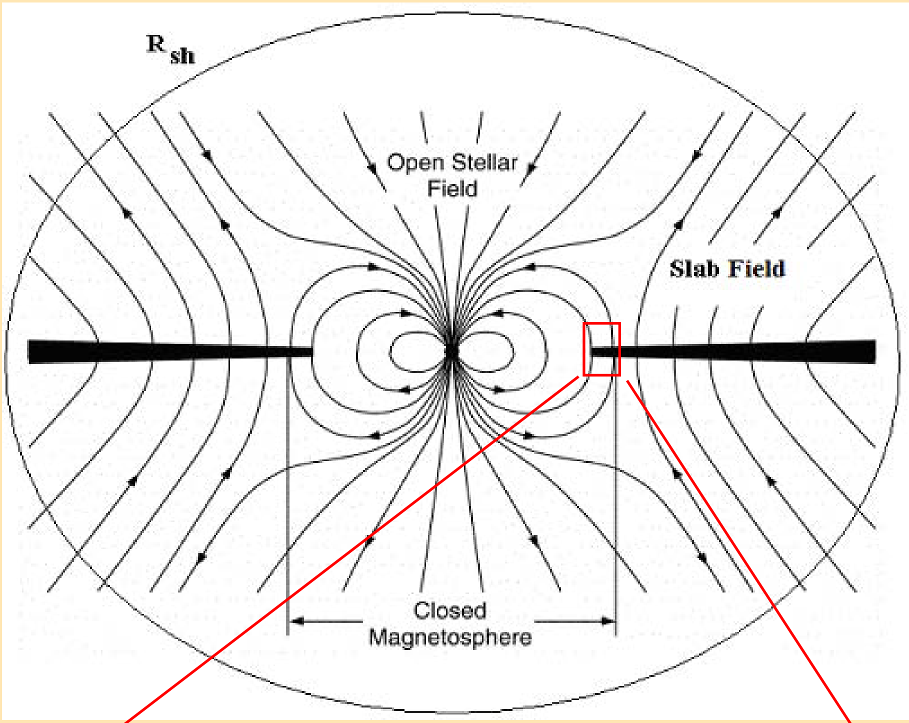
Density

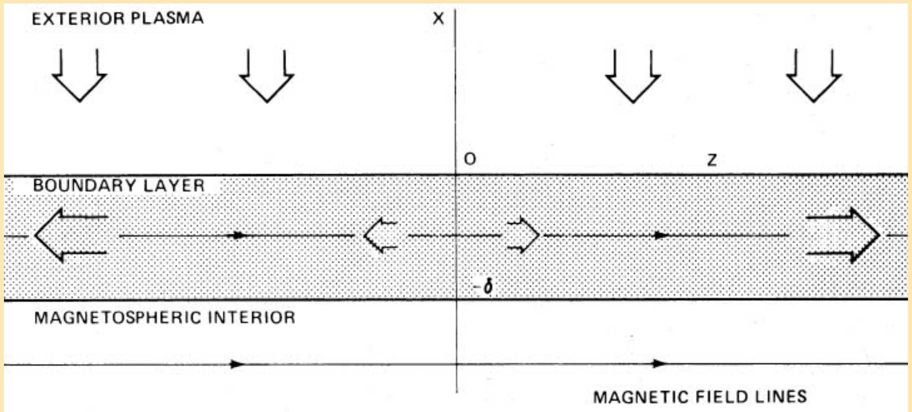


MAGLEV (Magnetic Levitation train system)

Ikhsanov (2012), MNRAS, 424, L39
Ikhsanov & Finger (2012), ApJ, 753, 1
Ikhsanov & Beskrovnaya (2012) Astronomy Reports, 56, 589

Magnetic-Levitation Accretion (MLA) onto a Neutron Star





Basic condition:

$$R_{sh} \; > \; \max\{r_A, r_{circ}\}$$

MAGLEV Disk:

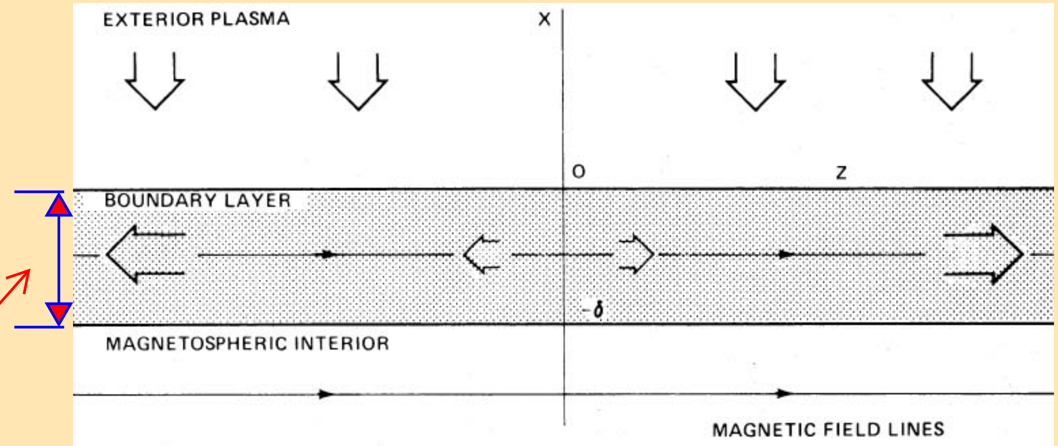
Outer radius is R_{sh}

Inner radius is $r_{ma} < r_A$

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

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



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

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

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**

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

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

Bisnovatyi-Kogan & Ikhsanov, Astronomy Reports, 58, 217 (2014) [arXiv:1401.2634]

Magnetic field of AXPs and SGRs in MLA scenario

- NS in the accretor state $r_{\rm ma} < r_{\rm cor}$

$$\mu < 10^{31}\,{\rm G\,cm^3} \times \alpha_{0.1}^{-1}\, T_6^{1/3}\, m^{-1/9}\, L_{34}^{2/3}\, R_6^{2/3} \left(\frac{P_{\rm s}}{5\,{\rm s}}\right)^{13/9}$$

- Spin-down rate $|K_{\rm ml}| \geq 2\pi I |\dot{\nu}_{\rm sd}|$

$$\mu \geq \left[\frac{2\pi I |\dot{\nu}_{\rm sd}|}{k_{\rm t}}\right]^{1/2} \left(r_{\rm ma}\, r_{\rm cor}\right)^{3/4}$$

Bisnovatyi-Kogan & Ikhsanov, Astronomy Reports, 58, 217 (2014) [arXiv:1401.2634]

Parameters of SGRs and AXPs in the MLA scenario

Name	P_s, c	$\lvert\dot{\nu}_{sd}\rvert$, 10^{-12} Hz s^{-1}	L_X, 10^{34} erg s^{-1}	B_*, 10^{12} G	r_{cor}, 10^8 cm	r_{ma}, 10^8 cm	a_p, 10^5 cm	T_{bb}, keV
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

- **MAGNETIC FIELD:** $B_* \sim (0.01 - 10) \times 10^{12}$ G
- **SOFT X-ray SPECTRUM** $kT \sim 0.3 - 1.4\,\mathrm{keV}$

Properties of AXPs and SGRs within the MLA scenario

- **Current state of AXPs:**

  A moderately magnetized ($\sim 10^{12}$ G) NS accreting from a fossil ML-disk.

  – Regular spin-down at the observed rate

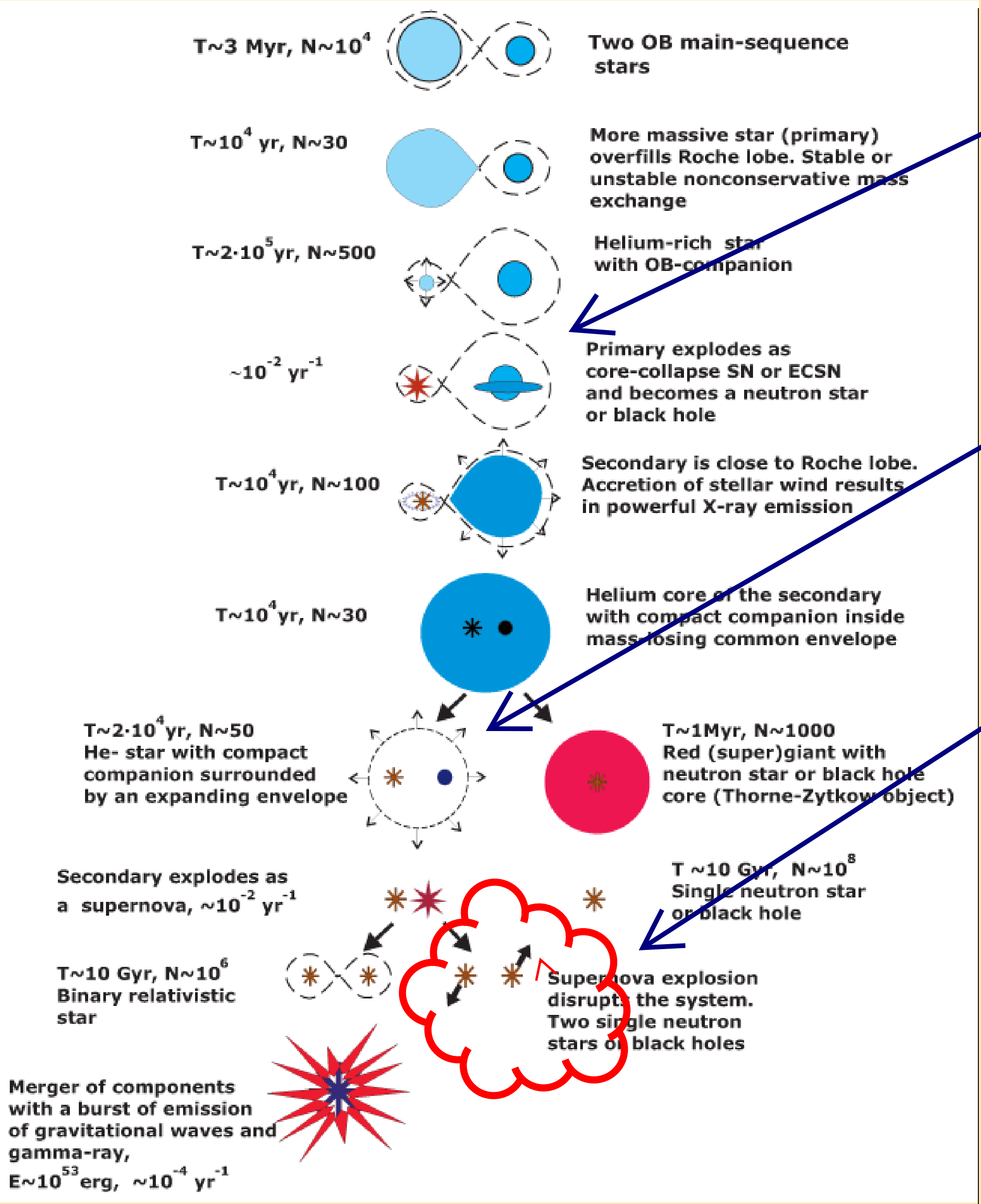
  – Soft X-ray spectrum

- **It remains to be explained:**

  1. Spin evolution in a previous epoch;
     – How could a moderately magnetized NS spin-down to a period of a few seconds on a timescale of only 1000 yr?
  2. Clustering of the spin periods of AXPs around $2 - 20$ s;
  3. Formation of the fossil ML-disk, and
  4. Bursting activity in soft gamma-rays

Bisnovatyi-Kogan & Ikhsanov, Astronomy Reports, 59, in press (2015) [arXiv:1407.6733v1]

AXPs as DESCENDANTS of High Mass X-ray Binaries



1. A NS forms in a Massive Binary System

   during the 1st SN explosion

2. Its spin period evolves on $\sim 10^6 - 10^7$ yr to

$$P_{\rm eq}^{\rm (Kd)} \simeq 3\,{\rm s}\ \times\ \mu_{30}^{6/7}\ m^{5/7}\ \dot{\mathfrak{M}}_{17}^{-3/7}$$

3. After 2nd SN explosion the system is disrupted

   the old ($\sim 10^6 - 10^7$ yr) NS becomes isolated

   – it is embedded into a SNR

   – it captures material from SN ejecta

   – it rotates with the period $P_{\rm eq}^{\rm (Kd)}$

   – it is spinning-down on $200 - 10^5$ yr

Mass of the fossil ML-disk is

$$M_{\rm d} = 4\pi \int_{r_{\rm ma}}^{R_{\rm sh}} \rho(r) h_{\rm z}(r) r dr$$

Disk parameters

- **Temperature** $T(r) = \left(\frac{\dot{\mathfrak{M}} G M_{\rm ns}}{4\pi r^3 \sigma_{\rm SB}}\right)^{1/4}$; $\quad T(r) \propto r^{-3/4}$
- **Halfthickness** $h_{\rm z}(r) = \left(\frac{k_{\rm B} T(r) r^3}{m_{\rm p} G M_{\rm ns}}\right)^{1/2}$; $\quad h_{\rm Z}(r) \propto r^{-9/8}$
- **Density** $\rho(r)\, c_{\rm s}^2(r) \propto r^{-5/2}$; $\quad \rho(r) \propto r^{-7/4}$

$$M_{\rm d} \simeq 7 \times 10^{-6}\, {\rm M}_{\odot} \times \alpha_{0.1}^{-7/3}\, \beta_0^{-11/12} \mu_{30}^{5/13}\, \dot{\mathfrak{M}}_{17}^{99/104}\, m^{25/52}\, c_7^{11/6}\, v_7^{-55/12}$$

The ML-disk can be formed from the most inner slowly moving part of the SN ejecta

Bisnovatyi-Kogan & Ikhsanov, Astronomy Reports, 58, 217 (2014) [arXiv:1401.2634v2]
Bisnovatyi-Kogan & Ikhsanov, Astronomy Reports, 59, in press (2015) [arXiv:1407.6733v1]

CONCLUSIONS

AXPs are descendants of HMXBs accreting from a residual MAGLEV-Disk

- **Neutron Stars rotating with the period $P_{\rm eq}^{\rm Kd}$ ~ a few seconds;**
- **Isolated and rather old** $\left(\sim 10^6 - 10^7\,{\rm yr}\right)$
- **Moderately magnetized** $\left(B_* \sim (0.01-10)\times 10^{12}\ \mathbf{G}\right)$

What powers activity of SGRs and AXPs in gamma-rays?

- *The energy source is located inside the Neutron Star*
  - **Magnetic energy in the crust is** $E_{\rm m} \leq 5\times 10^{46}\,B_{15}^2\,{\rm erg}$;
  - **Binding energy in the crust is** $E_{\rm nuc} \sim 10^{47}\,{\rm erg}$ **(for** $\rho \sim (0.4-10)\times 10^{11}\,{\rm g\,cm^{-3}}$**)**
- *Questions about the trigger and transmission are still open*