Discovery of coherent X-ray pulsations in the sub-luminous disk state of XSS J12270-4859

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The three states of millisecond pulsars

- **Accretion powered state**
  - X-ray outburst
  - L[X-rays] (erg/s) $10^{36}$

- **Sub-luminous disk state**
  - M28 I
  - XSS J12270-4859

- **Rotation powered state**
  - Radio/gamma-ray pulsations
  - $10^{31}$

- **Undetected**
  - $10^{32}$
  - $10^{33}$
  - $10^{34}$
  - $10^{35}$
  - $10^{36}$

- **L[γ-rays] (erg/s)**
  - $10^{34}$
  - $10^{35}$
The sub-luminous disk state

Accretion disk (Hα broad line);

X-ray luminosity $\sim 10^{33} - 10^{34}$ erg/s, variable,
Spectrum described by a power law with $\Gamma \sim 1.5$. No cut-off up to $\sim 80$ keV;

Radio bright emission with flat spectrum;

Gamma-ray ($>0.1$ Gev) luminosity $\sim 10^{34}$ erg/s; 5-10 times brighter than in radio pulsar state;

Systems can persist in the sub-luminous state for a decade.

What is powering the emission? Accretion or rotation power?
**XSS J12270-4859**

**Sub-luminous disk state**

X-ray luminosity $\sim 10^{34}$ erg/s

Fermi gamma-ray counterpart

same state during 2003-2013

[De Martino+2010, 2013; Saitou+2010; Hill+2011]

**Radio PSR state**

Very faint in X-rays ($\sim 10^{32}$) erg/s

No disk

[Bassa+2014, Bogdanov+2014, Roy+ 2014]
Sub-luminous disk state: X-ray pulsations

XMM-Newton detection of pulsations at the 1.7 ms spin period by performing a search around the radio PSR ephemerides

\[ A_{\text{RMS}} = (7.7 \pm 0.5)\% \]

\[ \frac{A_{\text{2nd}}}{A_{\text{1st}}} = 1.8 \]

Pulsations not detected in radio PSR state \((A_{\text{RMS}} < 7\%)\)

Pulsed flux \(\geq 10\) times larger than during radio PSR state \(\rightarrow\) accretion origin

Similar pulse shape in soft (0.5-2.5 keV) and hard (2.5-11 keV) XMM band

Sub-luminous disk state: X-ray pulsations

Pulsations detected only in **high state**

In **low** ($A_{\text{RMS}} < 5.8\%$) and **flaring state** ($A_{\text{RMS}} < 2.7\%$) no detection

Very similar behavior observed from PSR J1023+0038 in the sub-luminous disk state [Archibald et al. 2015]

Implications of X-ray pulsations

Pulsations detected at $L_X = 5 \times 10^{33} \text{erg/s}$
~100-1000 times lower than AMSPs

$$R_{in} = k_m R_A = k_m \left[ \frac{\mu^4}{2GM_s \dot{M}_d^2} \right]^{1/7}$$

The mass accretion rate on the NS surface is 100 times smaller than the one required to keep the magnetosphere inside the corotation radius.

$$(dM/dt)_{\text{disk}} \sim 100 (dM/dt)_{\text{NS}}$$ to have $R_{in} \sim R_{co}$

More than 95% of the inflowing mass ejected (e.g. through the propeller effect) or accumulated in the disk.
Propeller outflows

3d MHD simulations of propeller ejection of matter

Lii, Romanova+ 2014 – for a disk terminated close to the corotation surface, part of the inflowing mass manages to accrete and part is launched in an outflow.

→ Accretion and outflows can coexist
The gamma-ray emission

E_{\text{cut}} \sim \text{few GeV}
\rightarrow \text{radio pulsar models, GeV electrons of magnetospheric origin}
\rightarrow \text{propeller model, electrons accelerated at the turbulent disk-magnetospheric boundary}

Propeller hypothesis:
\rightarrow \text{synchrotron (up to MeV)}
\rightarrow \text{self-synchrotron Compton (up to GeV)}

A solution found for:
R_{\text{in}} = 1.8 \, R_{\text{co}}
(dM/dt)_{\text{disk}} = 2.4 \times 10^{-11} \, \text{M}_{\odot}/\text{yr} \sim 30 \, (dM/dt)_{\text{NS}}

(see Diego Torres talk later this morning)
Possible scenarios for the sub-luminous disk state:

- a rotation powered pulsar:
  - X-ray pulsations unlikely (not observed in the radio pulsar state);
  - Bolometric luminosity too high (close to or larger than spin down power);

- a purely accreting pulsar:
  - X-ray luminosity too low (predicted inner disc radius ~ 5 Rco);

- a propeller model (with a fraction of the mass accreted) accounts for the bolometric high energy luminosity and qualitatively explains the radio and the gamma-ray emission;

- Are all sub-luminous accretors pulsars? (need for new instruments)
A parallel session on X-ray binaries and pulsars

Abstract submission before September 15 at https://indico.cern.ch/event/336103/