Accretion and rotation power in millisecond pulsars

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Rotation powered (radio) pulsars

Credits: NASA's Goddard Space Flight Center
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The fundamental plane of pulsars

Millisecond pulsars
[Backer+ 1982 Nature]
- weakly magnetized
- often found in globular clusters → old systems
The fundamental plane of pulsars

Millisecond pulsars
[Backer+ 1982 Nature]
- weakly magnetized
- often found in globular clusters
  → old systems
- often in binaries

Spinning up neutron stars

Credits: NASA's Goddard Space Flight Center
A new transient in M28, IGR J18245-2452

IGR J18245-2452: a new hard X-ray transient discovered by INTEGRAL

ATel #4925; D. Eckert (ISDC, Switzerland), M. Del Santo, A. Bazzano (INAF/IAPS Rome, Italy), K. Watanabe (FGCU, USA), A. Paizis (INAF-Milano, Italy), E. Bozzo, C. Ferrigno (ISDC, Switzerland), I. Caballero (CEA, France), L Sidoli (INAF-IASF Milano, Italy), L. Kuiper (SRON, Netherlands)
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Credential Certification: E. Bozzo (enrico.bozzo@unige.ch)

Flux (20-100 keV) $\sim 9 \times 10^{-10}$ erg/cm$^2$/s

X-ray luminosity $\sim$ few $\times 10^{36}$ erg/s $\rightarrow$ accretion power
IGR J18245-2452 is an accreting millisecond pulsar

X-ray coherent pulsations detected at an amplitude of \( \sim 10\% \)

\[
P_{\text{spin}} = 3.9 \text{ ms} \\
P_{\text{orb}} = 11.0 \text{ hr} \\
M_{\text{comp}} \sim 0.2 \text{ M}_{\odot}
\]
Discovery of a transitional pulsar

**Radio PSR** (rotation power)  
**X-ray pulsar** (accretion power)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IGR J18245–2452</th>
<th>PSR J1824–24521</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Ascension (J2000)</td>
<td>$18^h 24^m 32.53(4)^a$</td>
<td></td>
</tr>
<tr>
<td>Declination (J2000)</td>
<td>$-24^\circ 52' 08.6(6)'$</td>
<td></td>
</tr>
<tr>
<td>Reference epoch (MJD)</td>
<td>56386.0</td>
<td></td>
</tr>
<tr>
<td>Spin period (ms)</td>
<td>3.931852641(2)</td>
<td>3.93185(1)</td>
</tr>
<tr>
<td>Spin period derivative</td>
<td>$&lt; 2 \times 10^{-17}$</td>
<td></td>
</tr>
<tr>
<td>RMS of pulse time delays (ms)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Orbital period (hr)</td>
<td>11.025781(2)</td>
<td>11.0258(2)</td>
</tr>
<tr>
<td>Projected semi-major axis (lt-s)</td>
<td>0.76591(1)</td>
<td>0.7658(1)</td>
</tr>
<tr>
<td>Epoch of zero mean anomaly (MJD)</td>
<td>56395.216889(5)</td>
<td></td>
</tr>
</tbody>
</table>

Papitto et al. 2013,  
*Nature*, 501, 517
Reactivation of the radio pulsar

Weak radio pulsar signal (~10-50 microJy) detected less than two weeks since the end of the X-ray outburst (GBT, PKS, WSRT)
M28: a decade of observations

**Radio pulsar** faint and irregularly eclipsed

Past **X-ray brightening** seen by Chandra - August 2008
Swings driven by mass in-flow rate variability

Low Mass in-flow rate:
Magnetic field dominates
→ rotation powered Radio PSR

Credits: NASA's Goddard Space Flight Center
Swings driven by mass in-flow rate variability

Low Mass in-flow rate:
Magnetic field dominates
→ rotation powered Radio PSR

High Mass in-flow rate:
Gravity dominates
→ accretion powered X-ray PSR

[Stella+ 1994; Campana+ 1998; Burderi+ 2001]
IGR J18245-2452: X-ray flux variability

Dramatic Flux and spectral variability point to the onset of a centrifugal barrier (propeller effect)

Dramatic Flux and spectral variability point to the onset of a centrifugal barrier (propeller effect)

Ferrigno, Bozzo, Papitto, Rea +
More transitional pulsars: PSR J1023+0038

A 1.7 ms **Radio PSR** in 2009

Accretion disk in 2000-01 (but faint in X-rays)

A state transition must have occurred, even if unobserved

**Archibald et al. 2009, Science**
June 2013, a new state transition

Radio pulsar disappears

5-fold increase of gamma-ray flux

PSR J1023+0038: June 2013, a new state transition

Broad double-peaked optical emission lines

Halpern+ 2013, Atel 5514
PSR J1023+0038: June 2013, a new state transition

10-fold increase of the X-ray flux
A third transitional pulsar: XSS J12270-4859

**Sub-luminous** ($\sim 10^{34}$ erg/s) in X-rays

- X-ray variability
- Low mass companion and disk
- Gamma-ray bright

Detected as a **Radio PSR**

- Very faint in X-rays ($\sim 10^{32}$) erg/s
- No disk

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

[Bassa+2014, Bogdanov+2014, Roy+ 2014]
The three states of millisecond pulsars

- **Accretion powered state**
  - X-ray pulsations
  - \( L_{\text{X-rays}} \) (erg/s): \( 10^{36} \) through \( 10^{35} \)

- **Sub-luminous disk state**
  - Radio/gamma-ray pulsations
  - \( L_{\gamma\text{-rays}} \) (erg/s): \( 10^{34} \) through \( 10^{33} \)

- **Rotation powered state**
  - Undetected
  - \( L_{\text{X-rays}} \) (erg/s): \( 10^{32} \) through \( 10^{31} \)
  - \( L_{\gamma\text{-rays}} \) (erg/s): \( 10^{33} \) through \( 10^{34} \)
Sub-luminous disk state: X-ray pulsations

PSR J1023+0038
Archibald et al. 2015

Pulsed flux ~10 times larger than during radio pulsar state
→ accretion powered pulsations

XSS J12270-4859 - Papitto et al. 2015

X-ray luminosity ~1000 times lower than in accreting ms pulsars
Implication of X-ray pulsations

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

$$(dM/dt)_{NS} \sim 10^{-2} (dM/dt)_{disk}$$

>95% of the inflowing mass ejected?
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
Radio brightness similar to BHs

A propeller model: the gamma-ray emission

$E_{\text{cut}} \sim \text{few GeV}$

$\rightarrow$ radio pulsar models, GeV electrons of magnetospheric origin

$\rightarrow$ propeller model, electrons accelerated at the turbulent disk-magnetospheric boundary

Accelerated electrons into a

**strongly magnetized** ($10^6$ G) and **relatively small** (~few tens of km) environment

$\rightarrow$ **synchrotron** (up to MeV)

$\rightarrow$ **self-synchrotron Compton** (up to GeV)

Good modelling for $R_{\text{in}} \sim 2 R_{\text{co}}$

The three states of millisecond pulsars

- **Accretion powered state**
  - X-ray pulsations
  - $L_{\text{X-rays}} = 10^{36}$ erg/s

- **Sub-luminous disk state**
  - Propeller outflows?
  - $L_{\gamma\text{-rays}}$ undetected

- **Rotation powered state**
  - Radio/gamma-ray pulsations
  - $L_{\gamma\text{-rays}} = 10^{34} - 10^{35}$ erg/s
Candidate transitional pulsars

**Eclipsing radio pulsars** [Fruchter+ 1988]

~50 known; bright gamma-ray sources
- Black widows ($M_c < 0.1$ Msun)
- Redbacks ($M_c \sim 0.2-0.7$ Msun)

The three transitional pulsars discovered so far are redbacks
Candidate transitional pulsars

**Accreting millisecond pulsars**

15 known [Wijnands & van der Klis 1998]

Weak X-ray transients (L_{peak} \sim 10^{36} \text{ erg/s})

A **radio PSR** turning on
during quiescence (L \sim 10^{32-33} \text{ erg/s})?

Reprocessed optical light [Burderi+2001, Campana+2002]


Orbital evolution [Di Salvo+ 2008, Patruno+2012]

...but no detection in radio, expect IGR J18245-2452

[Burgay+2003, Iacolina+2011, Xing+2012]
Does a radio pulsar turn on in quiescence?

Radio pulsar not detected, expect than for IGR J18245-2452
[Burgay+ 2003, Iacolina+ 2011] → enshrouding by intervening matter?

A candidate gamma-ray counterpart for SAX J1808.4-3658
[Xing+ 2015, de Oña Wilhelmi, Papitto+ 2015]

Accurate search for gamma-ray pulsations did not yield to a detection

$L_\gamma = (3.5 +/-.0.3) \times 10^{33} \text{ erg cm}^{-2}$
→ ~30% of the spin down power
Evolutionary scenarios

Is the transitional phase common? Which evolutionary channels?

[Graph showing evolutionary scenarios with markers for Classical MSP, Red Backs, Black Widows, and Accreting MSP, plotted against Orbital Period and Companion Mass (solar mass).]
An intermediate spin distribution

Papitto, Torres, Rea, Tauris, 2014, A&A
Tauris 2012, Science, 335, 561
Open questions

• What drives variations of the mass in-flow rate?
  Tidal interactions? Mass accumulation?

• Outflows during accretion powered stage
  (radio/X-ray correlations)?

• Origin of the gamma-ray emission during the sub-luminous
  accretion disk stage (propeller origin?)

• Are all millisecond pulsars in close binary systems transitional?
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