Swinging between accretion and rotation power in binary millisecond pulsars
Transitional millisecond pulsars

Bridging between pulsars powered by the rotation of their magnetic field (radio pulsars) and mass accretion (X-ray pulsars)

I. A full scale transition from a pulsar in M28, IGR J18245-2452

II. An intermediate case, PSR J1023+0038

III. Breaking news, a transition from XSS J12270-4859
Rotation powered pulsars: beacons from the radio to the gamma-rays
The fundamental plane of pulsars

Millisecond pulsars
[Backer+ 1982 Nature]
- weakly magnetised
- often in GCs
→ old systems
Recycling neutron stars

Millisecond pulsars
- old systems
  - often in binaries
Spinning up neutron stars
A new X-ray transient in M28 – IGR J18245-2452 (March 2013)

Globular Clusters are incubators of low mass X-ray binaries

INTEGRAL monitoring of transients

X-ray luminosity $\sim$ few $\times 10^{36}$ erg/s $\rightarrow$ accretion power
IGR J18245-2452 as a thermonuclear burster

Swift - XRT

[Papitto+ 2013, Linares 2013]
IGR J18245-2452 is an accreting millisecond pulsar

XMM-Newton
Pspin = 3.9 ms
Porb = 11.0 hr
[Papitto+ 2013]
IGR J18245-2452 was a rotation powered pulsar

The first system showing at different times, rotation and accretion powered pulses

Table 1: Spin and orbital parameters of IGR J18245–2452 and PSR J1824–2452I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IGR J18245–2452</th>
<th>PSR J1824–2452I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Ascension (J2000)</td>
<td>18h 24m 32.53(4)°</td>
<td></td>
</tr>
<tr>
<td>Declination (J2000)</td>
<td>-24° 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>3.93186(1)</td>
</tr>
<tr>
<td>Spin period derivative</td>
<td>&lt; 2 x 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>Eccentricity (e)</td>
<td>0.76591(1)</td>
<td>0.7658(1)</td>
</tr>
<tr>
<td>Inclination (°)</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Epoch anomaly (MJD)</td>
<td>56395.216889(5)</td>
<td></td>
</tr>
<tr>
<td>Mass (M☉)</td>
<td>2.2831(1) x 10^-3</td>
<td>2.282(1) x 10^-3</td>
</tr>
<tr>
<td>Radius (R☉)</td>
<td>0.174(3)</td>
<td>0.17(1)</td>
</tr>
<tr>
<td>Mass (M☉)</td>
<td>0.204(3)</td>
<td>0.20(1)</td>
</tr>
</tbody>
</table>
A few days after the end of the X-ray outburst, multiple detection of a weak radio pulsar (~10-50 microJy) – GBT, PKS, WSRT.
Radio pulsar faint and irregularly eclipsed

Past X-ray brightening seen by Chandra - August 2008
(more on this later)
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

**IGR J18245-2452: X-ray flux variability**

Very Low Frequency Noise

\[ P(f) \sim f^{-1.3} \]
IGR J18245-2452: X-ray flux variability

Noise of Accreting ms pulsars usually cut off at ~1 Hz

Here ~few x 10^{-4} Hz

Accretion rate fluctuations at the outer disk? [Lyubarskii 1997]
Pulsed fraction correlates with X-ray flux
Propeller inhibition of accretion?

Total inhibition of accretion never reached (pulse observed even at lowest flux)
IGR J18245-2452: patterns of variability

Average spectrum is hard (Comptonization with $\Gamma \sim 1.4$)

Larger average flux; constant hardness; stronger pulse profile

Lower average flux; variable hardness; weaker pulse profile

A stronger inhibition of accretion?
IGR J18245-2452: patterns of variability

Average spectrum is hard (Comptonization with $\Gamma \sim 1.4$)

Larger average flux; constant hardness; stronger pulse profile

Lower average flux; variable hardness; weaker pulse profile
Where to go next?
PSR J1023+0038

A Radio Pulsar/X-ray Binary Link

An accretion disk in 2000-01

Radio pulse are irregularly eclipsed (ongoing mass transfer)

A rotation powered pulsar nowadays

European Space Astronomy Center / ESA

MAD – 12.12.2013
PSR J1023+0038: June 2013, a forming accretion disc

Radio pulsar disappears

5-fold increase of gamma-ray flux
PSR J1023+0038: June 2013, a forming accretion disc

Broad double-peaked optical emission lines

Halpern+ 2013
PSR J1023+0038: June 2013, a forming accretion disc

Broad double-peaked optical emission lines

10x increase of the X-ray flux

[Patruno+ 2013]
At peak $\rightarrow L(\text{X-ray}) \sim 3 \times 10^{34}$ erg/s

With bolometric corrections equals the spin down power ($\rightarrow$ need for accretion power)

At minimum $\rightarrow L(\text{X-ray}) \lesssim 3 \times 10^{32}$ erg/s ($\rightarrow$ compatible with rotation-powered)
PSR J1023+0038: similarities with IGR J18245-2452

Rotation powered pulsar (~5E32 erg/s)

Propeller pulsar (~5E33 erg/s)

Chandra ACIS: 2008

European Space Astronomy Center / ESA

MAD – 12.12.2013
A gamma-ray bright low-mass X-ray binary: XSS J12270-4859

L(X-rays) $\sim 2 \times 10^{34} d_{2\text{kpc}}^2$ erg/s

L($\gamma$-rays) $\sim 2 \times 10^{34} d_{2\text{kpc}}^2$ erg/s

Flares and dips in soft X-rays

No pulsations detected in radio and X-rays

Optical continuum: K2-K5 star + disc

Broad H$\alpha$, H$\beta$ and He II detected indicate accretion disk

[De Martino+ 2010,2012; Saitou+ 2010; Hill+ 2011]
A millisecond pulsar in propeller?

Relativistic electrons up to $\gamma \sim 10^4$ from shocks at the magnetospheric boundary

**Synchrotron emission** ($B \sim 5 \times 10^6$ G)

**Synchrotron self-Compton emission** (electron density $\sim 10^{18}$ cm$^{-3}$)

The SED is reproduced for typical parameters of MSP ($B \sim 4 \times 10^8$ G; $R_{in} \sim 40$ km) and acceleration parameter $\sim 0.01-0.1$
Decrease of optical, X-ray and gamma-ray flux

A transition from an accretion (propeller) to a rotation pwd state?
Transitional pulsars to be searched among spiders

Mass transfer has to continue even when a radio pulsar is on

Pulsars ejecting transferred mass are recognized from radio eclipses
Millisecond pulsars have a relatively large spin down power

\[ \frac{dE}{dt} \sim \mu^2 \nu^4 \]

MSP are bright gamma-ray emitters

Gamma-rays in transitional pulsars also from inter-binary shocks

\[ \rightarrow \text{fundamental role of Fermi/LAT} \]
Accreting Millisecond Pulsars: a growing family

+ 2 intermittent pulsars (Aql X-1, SAX J1748.9-2021)

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

<table>
<thead>
<tr>
<th>Name</th>
<th>$P_{\text{Spin}}$ [ms]</th>
<th>$P_{\text{orb}}$ [min]</th>
<th>$M_{\text{c, min}}$ [M$_{\odot}$]</th>
<th>Discovered</th>
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<tbody>
<tr>
<td>SAX J1808.4-3658</td>
<td>2.5</td>
<td>120</td>
<td>0.043</td>
<td>Apr. 1998</td>
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<tr>
<td>XTE J1751-306</td>
<td>2.3</td>
<td>42</td>
<td>0.014</td>
<td>Apr. 2002</td>
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<tr>
<td>XTE J0929-314</td>
<td>5.4</td>
<td>44</td>
<td>0.083</td>
<td>Apr. 2002</td>
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<tr>
<td>XTE J1807-294</td>
<td>5.2</td>
<td>40</td>
<td>0.0066</td>
<td>Feb. 2003</td>
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<tr>
<td>XTE J1814-338</td>
<td>3.2</td>
<td>258</td>
<td>0.17</td>
<td>Jun. 2003</td>
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<tr>
<td>IGR J00291+5934</td>
<td>1.67</td>
<td>150</td>
<td>0.039</td>
<td>Dec. 2004</td>
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<td>HETE J1900.1-2455</td>
<td>2.6</td>
<td>84</td>
<td>0.016</td>
<td>Jun. 2005</td>
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<tr>
<td>Swift J1756.9-2508</td>
<td>5.5</td>
<td>54</td>
<td>0.007</td>
<td>Jun. 2007</td>
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<tr>
<td>NGC 6440 X-2</td>
<td>4.86</td>
<td>57</td>
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<td>Aug. 2009</td>
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<tr>
<td>IGR J17511-3057</td>
<td>4.1</td>
<td>208</td>
<td>0.13</td>
<td>Sep. 2009</td>
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<tr>
<td>Swift J1749.4-2807</td>
<td>1.9</td>
<td>530</td>
<td>0.6</td>
<td>Apr. 2010</td>
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<tr>
<td>IGR J17498-2921</td>
<td>2.5</td>
<td>230.4</td>
<td>0.17</td>
<td>Aug 2011</td>
</tr>
<tr>
<td>IGR J18245-2452</td>
<td>3.9</td>
<td>661.5</td>
<td>0.17</td>
<td>March 2013</td>
</tr>
</tbody>
</table>
Accreting Millisecond Pulsars: a realm of transients

A radio pulsar switching on during X-ray quiescence?

[Stella+ 1994; Campana+ 1998; Burderi+ 2001]
Accreting millisecond pulsars: irradiation of the companion

The spin down power of a radio pulsar illuminates the companion [Burderi+2003; Campana+2004, D'Avanzo+ 2009,2011; Cornelisse+ 2009]
Accreting millisecond pulsars: spin down during quiescence

[Hartman+2008; Hartman+2009; Papitto+ 2010; Hartman+ 2010]
Accreting millisecond pulsars: fast orbital evolution

Mass ejection during quiescence [Di Salvo+ 2008; Burderi+ 2009]

Short term transfer of angular momentum between donor and orbit [Hartman+ 2008, 2009; Patruno+ 2013]
Searches for rotation powered pulsations during quiescence in radio (Burgay+ 2003; Iacolina+ 2011) and gamma-ray (Xing+ 2012) so far not successful.

Absorption and smearing of radio pulses is the largest for close systems (IGR J18245-2452 is the AMSP with the longest orbital period).

Increase statistics of gamma-ray photons, while keeping updated ephemerides.
IGR J18245-2821 is the definitive proof of an evolutionary link between accreting and rotation powered ms pulsars

Fast (~days) swinging between accretion and rotation powered states

Transitions set by variations of the mass accretion rate

A puzzling light curve, hardness and pulse variability. A propeller interpretation?