Transitional Millisecond Pulsar Binaries

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**Millisecond Pulsars**

**AMXPs**
Accretion-power X-ray ms Pulsars
X-ray bright & radio quiet

**RMSPs**
Rotation-power radio ms Pulsars
Radio loud & X-ray faint
Millisecond pulsars:
- Low fields: $B \approx 10^8 - 10^9\text{G}$
- Many in Globular Clusters
- Most in found in binaries
- Spin-up due to accretion

Recycling scenario:
AMXPs believed to be progenitors of RMPS (Baker 1982; Alpar et al. 1982)
What link between LMXBs and radio MSP?

**LMXBs hosting AMXPs**

- Subclass of LMXBs: 19 systems - $P_{\text{spin}} < 10\text{ms}$; $B \approx 10^8 - 10^9 \text{G}$ (Patruno & Watts 2012)

- Long quiescence: $L_x \approx 10^{31} - 10^{34} \text{erg/s}$

- Occasional outbursts: $\Delta T \approx \text{days to yrs}$ $L_x \approx 10^{36} \text{erg/s}$

- Compact binaries: $P_{\text{orb}} < 1 \text{ d}$

- RLOF Donors: MS, CO/He WD - $M_2 < 0.2M_\odot$

- 10 Nuclear-power MSPs: Type-I bursts - Quasi-coherent Oscillations (Watts 2012)
What link between LMXBs and radio MSP?

Rotation-power ms pulsars (RMSPs)

- ≈ 340 radio MSPs: $P_{\text{spin}} < 30\text{ms}$; $B \approx 10^7 - 10^9\text{G}$; $E_{\text{spin-down}} \approx 10^{34} - 10^{35}\text{erg/s}$

- ≈ 200 are in compact binaries: $P_{\text{orb}} < 1\text{d}$

- ≈ 60 show irregular radio eclipses $\rightarrow$ mass loss from ablated donor star:
  - 38 “Black widows” (BW) - $M_2 < 0.04M_\odot$ (degenerate)
  - 22 “Redbacks” (RB) - $M_2 \approx 0.1 - 0.4\ M_\odot$ (MS) (Roberts 2011, 2013)

[ Listen M. Roberts - BINARY III on Wed. afternoon]

- ≈ 50 detected as Gamma-ray Fermi-LAT sources

- BW believed to descend from RB but not all RB evolve into BW (Benvenuto 2014)
**PSRJ 1023+0038: the missing link binary MSP**

CV-like optical spectrum!

Optical flickering

Variable radio source

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Bond et al. 2002
Szkody et al. 2003
**PSRJ 1023+0038:** the missing link binary MSP

- CV-like spectrum!
- No Accretion disc
- Optical flickering
- Optical modulation @4.75h
- Variable radio source
- Variable X-rays

2000 2001 2002 2003 2004

Bond et al. 2002
Szkody et al. 2003
Would et al. 2002; Homer et al. 2004,
Thorstensen&Armstrong2005
**PSRJ 1023+0038**: the missing link binary MSP

Variable radio source
Optical flickering
CV-like spectrum

No Accretion disc
Optical modulation @4.75h
Variable X-rays

Change of State

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&Armstrong 2005
PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @4.75h

Archibald et al. 2009, Science

LMXB

RMSP

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen&Halpern2005


time (yrs)
**PSRJ 1023+0038**: the missing link binary MSP

- 1.69ms Radio Pulsar
  - Radio Eclipses @4.75h
- Marginal γ–ray Pulses@ 1.69ms
- X-ray Pulses @ 1.69ms

LMXB  →  RMSP

- 2000
- 2001
- 2002
- 2003
- 2004

Archibald et al. 2010, 2013
PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @4.75h

Marginal γ-ray Pulses@ 1.69ms

X-ray Pulses @ 1.69ms
X-ray modulation @ 4.75h

LMXB  RMSP

2000  2001  2002  2003  2004

Archibald et al. 2010, 2013
Bogdanov et al. 2011
Tendulkar et al. 2014

Chandra  0.3-8 keV  P=4.75h

2001 (yrs)  

0.06  0.05  0.04  0.03  0.02  0.01  0.00

0.07  0.06  0.05  0.04  0.03  0.02  0.01

0.3-8 keV  1.9-6 keV  0.3-4.9 keV

Marginal γ-ray Pulses@
X-ray Pulses@
X-ray modulation @
PSRJ 1023+0038: the missing link binary MSP

1.69ms Radio Pulsar
Radio Eclipses @ 4.8h
7ms X-ray Pulse @ 4.8h
Marginal γ-ray Pulse @ 1.7ms

Archibald et al. 2009, Science

Recycling Scenario

LMXB

RMSP

Bond et al. 2002
Szkody et al. 2003

Would et al. 2002;
Homer et al. 2004,
Thorstensen & 2005

Archibald et al. 2010, 2013
**IGR J18245-2452: A transient in the GC M28**

Papitto et al. 2013, Nature

An AMXP discovered in outburst

March 28, 2013

Lx $\approx 1-4 \times 10^{36}$ erg/s

X-ray Pulses (4-16%) @ 3.9ms

Porb = 11. 0h

Thermonuclear Bursts

Peculiar short term X-ray variability
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

Papitto et al. 2013, Nature

Variable X-ray source

ACIS – S  HRC  Chandra ACIS-S  HRC


time (yrs)
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

Papitto et al. 2013, Nature

Variable X-ray source

ATNF Catalog: 3.9ms radio pulsar
The first swinging MSP binary

PSRJ1824-2452 / IGR J18245-2452

Papitto et al. 2013, Nature

Variability

ACIS – S
HRC

2002
2006

PSRJ1824-2452

ATNF Catalog 3.9ms radio pulsar

no radio pulsar

radio pulsar

2002
2009
2006
2008
2013

March-April

radio pulsar

Variable X-ray source

RMSP
AMXP

$\log (L_x \text{ (erg/s)})$

$\log (I_{\text{radio pulse}} \text{ (erg/s)})$

Time (yrs)
The first swinging MSP binary

Peculiar X-ray Variability in Outburst

\[
\Gamma \approx 1.6 \rightarrow 1.4
\]

High Mode

\[
\Gamma \approx 1.7 \rightarrow 1.1
\]

Low Mode

Ferrigno et al. 2014

0.3-3.5keV

3.5-11keV

HR

XMM-Newton
The first swinging MSP binary

Peculiar X-ray Variability also in a sub-luminous state

Mode switching

Accretion ↔ Inhibition of accretion

Linares et al. 2014
Papitto et al 2013
Ferrigno et al. 2014
**PSR J1023+0038: a new state transition in 2013**

- **RMSP** → **LMXB**

- $L_\gamma \approx 0.1 \rightarrow 1.2 \times 10^{34} \text{ erg/s}$
- $L_x \approx 0.5 \rightarrow 6 \times 10^{33} \text{ erg/s}$
- $V_{\text{Opt}} \approx 17.5 \rightarrow 16.2 \text{ mag}$

- **Accretion Disc**

**Timeline:**
- 2004: Stappers et al. 2014
- Mid 2013: Tendulkar et al. 2014
- 2017: Patruno et al. 2014, Bogdanov et al. 2015
**PSR J1023+0038:** the LMXB state

X-ray Tri-modal behaviour:
- Erratic Flares $\approx$ tens mins up to 10 hr
- Erratic Dips = Low Mode $\approx$ secs-mins
- Persistent level = High Mode

Tendulkar et al. 2014
Bogdanov et al. 2015
**PSR J1023+0038: the LMXB state**

XMM-Newton 2013-2014

Mode switching in a few sec

X-ray pulses in high mode only

Bogdanov et al. 2015
Archibald et al. 2015
**PSR J1023+0038: the LMXB state**

No substantial spectral variability

but Soft & hard dips $\rightarrow$ subtle changes

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**XMM-Newton**

PSRJ1023+0038 LMXB STATE

**Rate [0.3-10keV]**

**HR [0.3-2 / 3-10keV]**

[Graphs showing time series and hardness ratio plots]
**PSR J1023+0038: the LMXB state**

Average spectrum featureless: $\Gamma = 1.7$ softer than RMSP state $\Gamma = 1.26$

No substantial spectral variability - No thermal component

Flare: $\Gamma \approx 1.7$

High: $\Gamma \approx 1.7$

Low: $\Gamma \approx 1.8$

Dominated by outflowing matter?

Bogdanov et al. 2015
**XSS J1227-4859**: a peculiar hard low-luminosity source

CV-like optical spectrum!

Variable Hard X-rays

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Masetti et al. 2006
Sazonov & Revnivtsev 2008
**XSS J1227-4859**: a peculiar hard low-luminosity source

- CV-like optical spectrum!
- Variable Hard X-rays
- Erratic X-ray - UV/optical variability
- Fermi-LAT/XMM-Newton association

**Timeline**:
- 2006: Masetti et al. 2006
- 2009: de Martino et al. 2010
- 2010: Time (yrs)
**XSS J1227-4859:** a peculiar hard low-luminosity source

CV-like optical spectrum!

Variable Hard X-rays

Erratic X-ray - UV/optical variability

Weak radio source

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**XMM-Newton**

- **HR**
- **U**
- **UV**

**ATCA 9GHz**

**2006**

Masetti et al. 2006

Sazonov & Revnivtsev 2008

**2007**

**2009**

de Martino et al. 2010, 2013

Saitou et al. 2010

Hill et al. 2011

**2010**

time (yrs)
**XSS J1227-4859: the LMXB state**

**Tri-modal behaviour:**

Sporadic Flares ≈ mins

Erratic Dips = Low Mode ≈ secs-mins

Persistent level = High Mode

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de Martino et al. 2010, 2013
XSS J1227-4859: the LMXB state

No substantial spectral variability
but Soft & hard dips → subtle changes

de Martino et al. 2010, 2013
XSS J1227-4859: the LMXB state

Average spectrum featureless: $\Gamma = 1.7$

No substantial spectral variability except in Post-flare Dips

Flare: $\Gamma \approx 1.7$

High: $\Gamma \approx 1.6$

Dips: $\Gamma \approx 1.7$

Post-flare Dips: $\Gamma \approx 0.7$ + PCF

de Martino et al. 2010, 2013
XSS J1227-4859: a late recognised transitional MSP binary

Disc  ⇋  Disc-free

\[ L_y \approx 1.1 \rightarrow 0.4 \times 10^{34} \text{ erg/s} \]

\[ L_x \approx 6 \rightarrow 0.2 \times 10^{33} \text{ erg/s} \]

\[ V_{\text{Opt}} \approx 16 \rightarrow 18 \text{ mag} \]

G-type optical spectrum

No disc

Bassa et al. 2014
Bogdanov et al. 2014
de Martino et al. 2014
Torres et al. 2017
**XSS J1227-4859**: a late recognised transitional MSP binary

Roy et al. 2015
**XSS J1227-4859**: a late recognised transitional MSP binary

- LMXB → RMSP
- Gamma-ray PSR @ 1.69ms
- Fermi-LAT > 100MeV
- 1.5 GHz


- References:
  - Roy et al. 2015
  - Johnson et al. 2015
**XSS J1227-4859:** now a Redback irradiated by Intrabinary Shock

No X-ray Pulses @ 1.69ms
X-ray modulation @ 6.91h
Optical modulation @ 6.91h

**XMM-Newton**

0.3-12keV

**NuSTAR**

3-79 keV

de Martino et al 2015
Papitto et al. 2015, 2017 inprep
**XSS J1227-4859**: now a Redback irradiated by Intrabinary Shock

- Intrabinary Shock dominates X-rays
- Light Curve Shape depends on wind momentum ratio

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**XMM-Newton** 0.3-12keV

**NuSTAR** 3-79 keV

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Romani & Sanchez 2016

de Martino et al 2015

Papitto et al. 2015, 2017 inprep
**XSS J1227-4859**: a late recognised transitional MSP binary

**XMM-Newton 2009-2011**

**X-ray pulses in high mode only**

**Mode switching**

![Graph showing luminosity (0.3-10keV) in erg/s]

- **PSR?**
- **transition**
- **Flares**
- **Low**
- **High**

Luminosity (0.3-10keV) (erg/s)

- **A ≈ 8%** High
- **A < 2%** Flares 3σ
- **A < 5.9 %** Low 3σ

Papitto et al. 2015
• Mass inflow rate should be larger to have pulsations

• X-rays do not only trace the mass accretion rate on NS

• Advected energy in the disc powers propeller

[ Listen Papitto – Binaries VI – Thurs. afternoon]

\[ \dot{M}_{\text{MSP}} \approx R_{\text{mag}} \alpha M_{\text{acc}}^{-2/7} \mu_{B}^{4/7} \]

\[ R_{\text{in}} \leq R_{\text{co}} \leq R_{\text{LC}} \quad \text{Accretion state} \]

\[ R_{\text{CO}} < R_{\text{in}} < R_{\text{LC}} \quad \text{Accretion inhibited} \]

\[ R_{\text{in}} > R_{\text{LC}} \quad \text{Radio Pulsar state} \]

Linares 2014
Campana et al. 1998
Romanova et al. 2014, 2017
Papitto & Torres 2014, 2015
Outflows in tMSPs

3-D MHD - Propeller driven winds & Jets

Romanova et al. 2014, 2017

Strong propeller: $\omega_s = \Omega_*/\Omega_k \gg 1$

2 Component Outflow

- Slow dense conical wind
- Low-density high-velocity jet

Accretion onto NS still possible
Observational Evidence?

- **Radio variability** (mins)
- **Radio flat-inverted slope:**
  \[ S_\nu \approx \nu^\alpha, \quad \alpha \approx 0.05 \]

- tMSPs closer to BH than NS
- tMSPs radio louder than other NS

\[ \rightarrow \quad \text{Compact jet in tMSPs likely} \]

Few simultaneous X-ray & Radio obs

Longer simultaneous coverage needed!

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**Outflows in tMSP**

**Hard state NS & BH**

- PSRJ1023: from Deller et al. 2015,
- XSS1227: from de Martino et al. 2015,
- IGR1824: from Ferrigno et al. 2014
tMSPs: an intermediate or atypical evolutionary stage?

Need to find more!

Ongoing Intense Activities:

• X-ray, Radio & Optical search of counterparts of FERMI-LAT Unidentified sources

  → RBs, BWs and tMSPs candidates

3FGLJ1544-1128 / RXJ1544-1128  Bogdanov & Halpern 2015

• Long-term X-ray & Optical monitoring of known Radio Eclipsing RB

• X-ray deep observations of AMXPs in quiescence may reveal odd modes
Stay tuned!

Thanks: