Millisecond Pulsar $\gamma$-ray Emission: A Sign of Binary Interaction?

Anne Archibald (archibald@astron.nl)

ASTRON

2014 October 22
Pulsars

Millisecond pulsars form a distinct population
- Low magnetic field
- Mostly binary
- Very long-lived
- Can be energetic

Formation model: recycling
- Details remain murky

Pulsars from the ATNF catalog

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The pulsar mechanism generically produces γ-rays
Millisecond pulsar γ-ray efficiency not unusual
Pulsars are steady γ-ray sources (mostly)
There are two peculiar classes of MSPs, collectively called “spiders”:

- MSPs in tight binary orbits ($\lesssim 1$ day) with low-mass companions
- Show signs of binary interaction, including some or all of:
  - Radio eclipses (variable, frequency-dependent)
  - Companion irradiation
  - X-rays from an intrabinary shock
  - Orbital period variations

- Divided based on companion mass:
  - Black widow: $\lesssim 0.1M_\odot$, degenerate, not Roche-lobe-filling
  - Redback: $\sim 0.1–0.6M_\odot$, main-sequence-like, usually Roche-lobe-filling
Spiders

- Few were known until recently
- Many new spiders found based on Fermi observations
  - High $\dot{E}$?
  - Selection effects?
  - Non-pulsar $\gamma$-rays?

Redbacks (red) and black widows (black)
Transition objects

- Three objects have been observed to move between radio pulsar and accretion-disc states:
  - PSR J1023+0038: radio pulsar to accretion-disc state (plus past accretion-disc episode)
  - M28I: radio pulsar to polar-cap accretion back to radio pulsar
  - XSS J12270−4859: faint accretion-disc state to radio pulsar
M28I

- **Radio state:**
  - Eclipsing radio pulsar
  - $L_X \lesssim 10^{32}$ erg/s

- **Accretion-disc state:**
  - X-ray pulsations
  - $L_X \approx 10^{36}$ erg/s
  - Thermonuclear bursts
  - Continuum radio emission
  - Peculiar rapid variability
  - No radio pulsations

- Transitions seem to take $< \text{days to months}$
- Evidence for multiple transitions in the last few years
- 5.5 kpc

X-ray image of the core of M28I before and during activity, from Papitto et al. 2013
Radio state:
- Eclipsing radio pulsar
- Mildly heated G-coloured companion
- Absorption-line spectrum
- Orbital period variations
- $L_X \approx 3 \times 10^{32}$ erg/s
- X-ray pulsations
- X-ray intrabinary shock
- $\gamma$-ray pulsations

1.35 kpc
PSR J1023+0038

Historical episode:
- Observed only optically
- Occurred in 2000/2001
- Lasted 1.5–3 years
- Optical brightening, flickering
- Emission line spectrum with double-peaked lines
- X-ray upper limit \( \sim 5 \times 10^{33} \) erg/s

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1.35 kpc
Current accretion-disc state:

- Began late 2013 June
- Radio pulsations disappeared
- Emission line spectrum with double-peaked lines
- X-rays variable state-switching \(2.5 \times 10^{33}\) erg/s
- Variable flat-spectrum radio continuum suggestive of a jet
- \(\gamma\)-ray brightened by a factor of 5

1.35 kpc
Accretion-disc state:
- X-ray variability
- $L_X \sim 10^{35}$ erg/s
- Emission-line spectrum
- $\gamma$-ray emission

Current radio-pulsar state:
- $L_X \sim 10^{32}$ erg/s
- Eclipsing radio pulsar
- Mid-G donor star (no emission lines)
- Decrease in $\gamma$-ray emission by a factor of 1.5-2

1.4–3.6 kpc
What is happening in these transition objects?

- Radio pulsar states are typical redbacks
- M28I accretion-disc state nearly normal AMXP
  - M28I is too far to easily study faint accretion states
- J1023, XSS J12270 accretion-disc states peculiar:
  - Very low luminosity — propeller mode?
  - $\gamma$-ray emission
  - J1023 state-switching
- What triggers state switching?
  - Orbital period variations possibly due to companion shape changes may produce Roche-lobe overflow
  - Radio ejection mechanism may produce bistable state
Key puzzles

- Why have these systems stopped being full-fledged LMXBs?
- Do other LMXBs enter such low-luminosity accretion-disc states?
- What is going on in these peculiar accretion-disc states?
- How do these systems produce $\gamma$-rays?
- What is the ultimate fate of these systems?