The radio emission of the transitional millisecond pulsar binary PSR J1023+0038 in an LMXB state

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With thanks to

- Participants across many institutes:
  - Adam Deller, Anne Archibald, Jason Hessels, Gemma Janssen, Cees Bassa, George Heald, Nicolas Vilchez (ASTRON)
  - James Miller-Jones (Curtin)
  - Alessandro Patruno, Caroline D'Angelo (Leiden)
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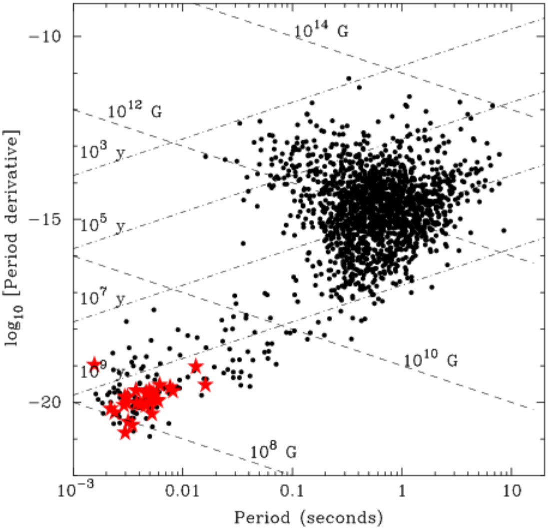
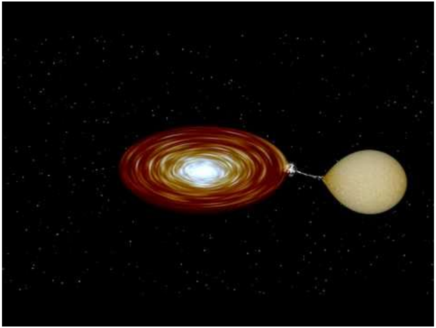
  - Shriharsh Tendulkar (Caltech)
  - Rudy Wijnands (Amsterdam)
- For more details see:
  - Deller, A. T., Moldón, J., Miller-Jones, J. C. A., et al. 2014, arXiv:1412.5155
  - Bogdanov, S., Archibald, A. M., Bassa, C., et al. A&A (in press), arXiv:1412.5145

Millisecond pulsars

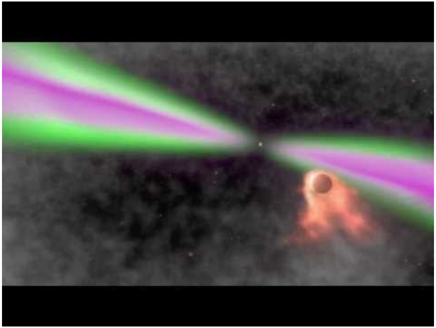
- A subset of pulsars have periods $\lesssim 20$ ms and magnetic fields of $\sim 10^8$ G.
- They are usually found in binary systems.
- They are old system spun up by a acreting "recycling" process.



Two stages of the recycling process

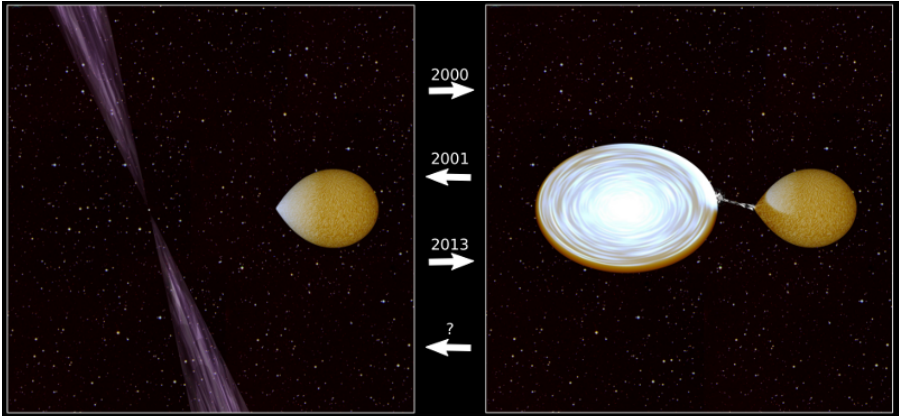


Accreting low-mass X-ray binary



Millisecond pulsar
(black widow, redback, isolated)

PSR J1023+0038 - The missing link



- The system was in a MSP state for 12 years.
- Currently it is in an accreting state.
- Other systems with state change: M28I, XSS J12270-4859

Scientific motivation

- Formation and population of millisecond pulsars:
  - Neutron star equation of state.
  - High-accuracy long-term timing.
  - General relativity tests. Post-newtonian parametrization.
  - Gravitational wave detection.
  - Binary evolution.
- tMSP accreting state:
  - Low-acretion rates in NS LMXB and jet formation.
  - Gamma-ray production.
- tMSP non-accreting state:
  - Ablation of companion.
  - X-ray and gamma-ray emission.
  - Scaled-down version of gamma-ray binaries.
  - Accurate orbital parameters thanks to pulsar timing.

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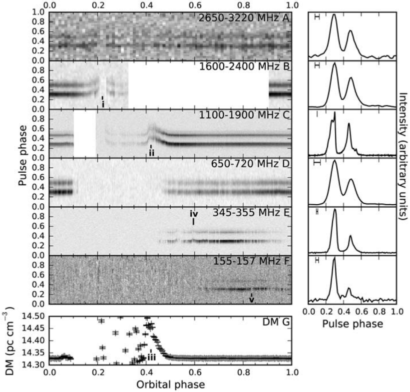
The system PSR J1023+0038

System parameters from pulsar timing

TABLE 1
LONG-TERM EPHEMERIS FOR J1023

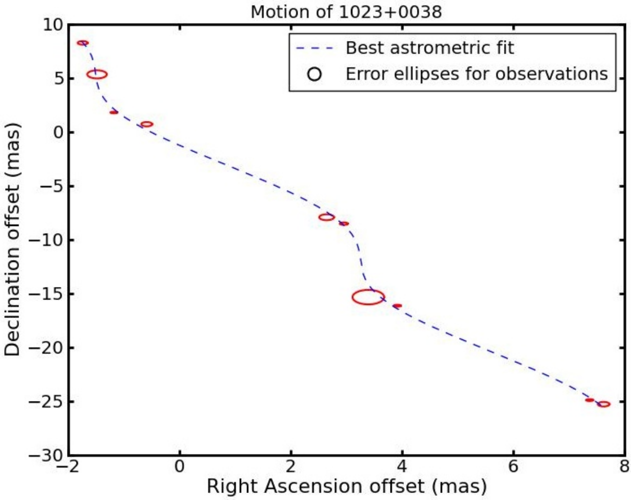
Fit and data-set	
Pulsar name	J1023+0038
MJD range	54766.5—56146.6
Number of TOAs	7478
Rms timing residual (μs)	114.0
Weighted fit	No
Measured Quantities	
Pulse frequency, ν (s^{-1})	592.42145906986(10)
First derivative of pulse frequency, $\dot{\nu}$ (s^{-2})	$-2.432(3)\times10^{-15}$
Orbital period, P_b (d)	0.1980963569(3)
Epoch of periastron, T_0 (MJD)	54905.9713992(3)
Projected semi-major axis of orbit, x (lt-s)	0.343343(3)
First derivative of orbital period, $\dot{P}_b$	$-7.32(6)\times10^{-11}$
Set Quantities	
Right ascension, α	10:23:47.687198
Declination, δ	+00:38:40.84551
Epoch of frequency determination (MJD)	54906
Epoch of position determination (MJD)	54995
Dispersion measure, DM ($cm^{-3}pc$)	14.3308
Proper motion in right ascension, μ_α ($mas\,yr^{-1}$)	4.76
Proper motion in declination, μ_δ ($mas\,yr^{-1}$)	−17.34
Parallax, π (mas)	0.000731
Orbital eccentricity, e	0



[Archibald et al. 2009]

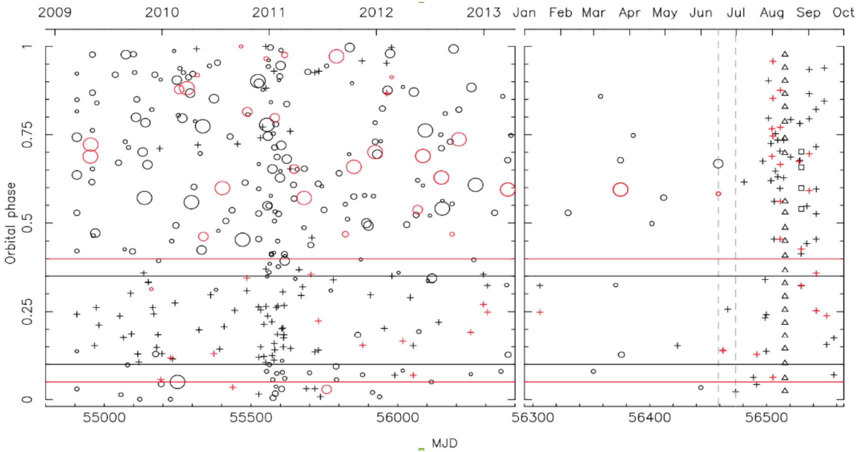
- Orbital period 4.8 h. Pulsar period 1.7 ms.
- Companion is a 0.2 $M_\odot$ star.
- Shows radio eclipses, dispersion measure (DM) variations, and orbital period variations.

Distance to PSR J1023+0038



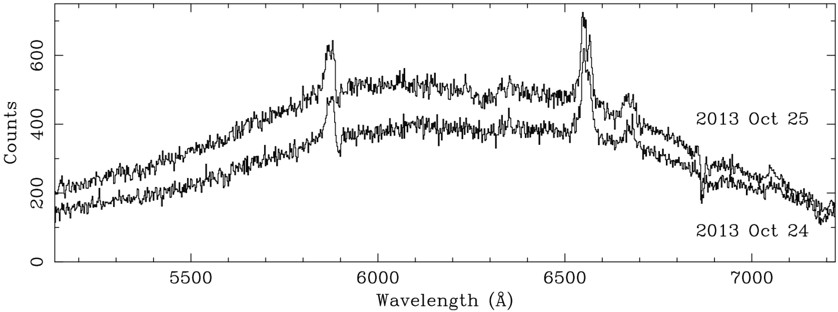
- Radio VLBI distance. $d = 1370 \pm 40$ pc. [Deller et al. 2012]

Pulses disappear in 2013!



- Radio MSP disappears in June 2013. [Stappers et al. 2014]
- Open circles are pulsation detections, crosses are non-detections

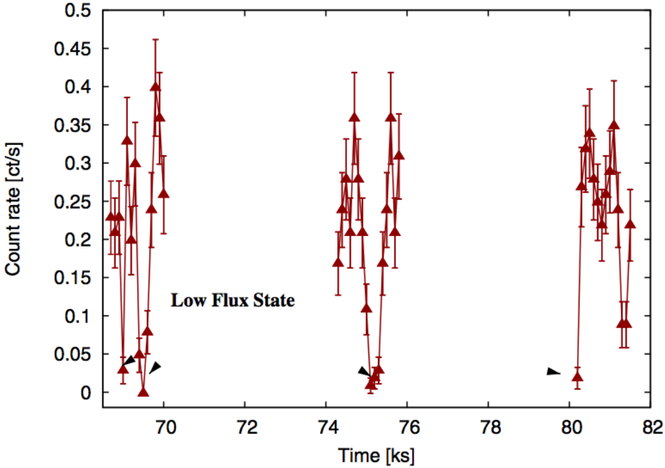
New state - Optical



[Halpern et al. 2013]

- Optical spectra show brightening, double-peaked emission lines.

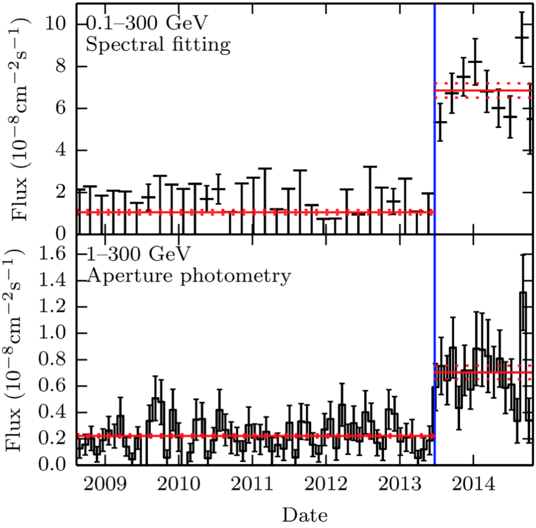
New state - X-rays



[Patruno et al. 2014]

- X-ray shows increased by factor > 20 to $\sim 3 \times 10^{33}$ erg/s. Flickering.

New state - Gamma-rays



[Stappers et al. 2014]

- *Fermi* flux suddenly increased by a factor of 5.

What do we want to know?

- What do we want to know?
  - Is there radio emission?
  - Is the pulsar mechanism quenched?
  - What is the accretion state of the system?
  - Can we explain the gamma-ray emission?
- What observations did we conducted?
  - Extensive multiwavelength campaign.
  - Detailed radio monitoring.

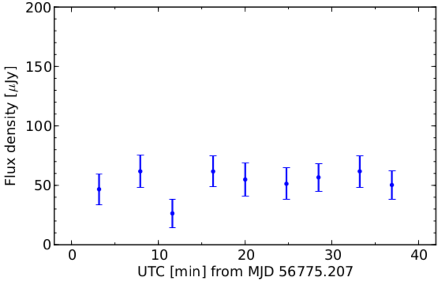
Radio monitoring

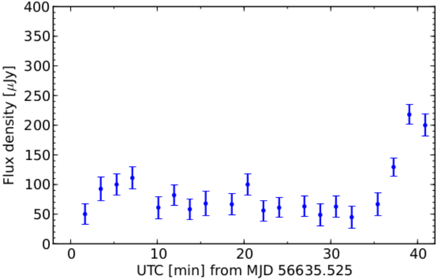
[Deller, A. T., Moldón, J., Miller-Jones, J. C. A., et al. 2014, arXiv:1412.5155]

Extensive radio campaign

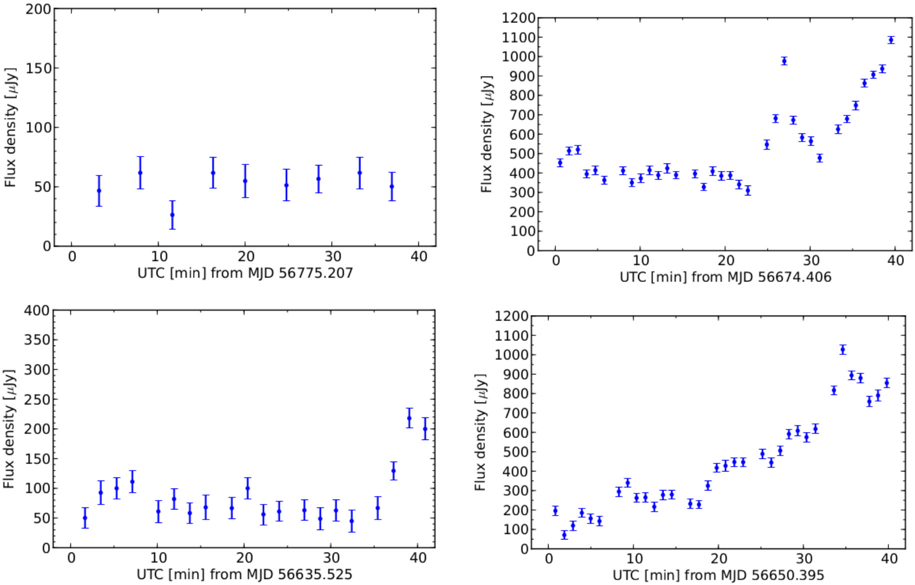
Start MJD	Duration (hours)	Instrument	Frequency range (GHz)
56606.68	2.0	VLA (B)	4.5 – 5.5, 6.5 – 7.5
56607.18	5.0	LOFAR	0.115 – 0.162
56607.57	1.0	VLA (B)	2.0 – 4.0
56609.09	7.5	EVN	4.93 – 5.05
56635.52	1.0	VLA (B)	8.0 – 12.0
56650.39	1.0	VLA (B)	8.0 – 12.0
56664.31	1.0	VLA (B)	8.0 – 12.0
56674.40	1.0	VLA (B)	8.0 – 12.0
56679.46	2.5	VLA (BnA)	1.0 – 2.0, 4.0 – 8.0, 12.0 – 18.0
56688.38	1.0	VLA (BnA)	8.0 – 12.0
56701.21	1.0	VLA (BnA)	8.0 – 12.0
56723.35	1.0	VLA (A)	8.0 – 12.0
56735.28	1.0	VLA (A)	8.0 – 12.0
56748.06	1.0	VLA (A)	8.0 – 12.0
56775.20	1.0	VLA (A)	8.0 – 12.0

Intraday lightcurves

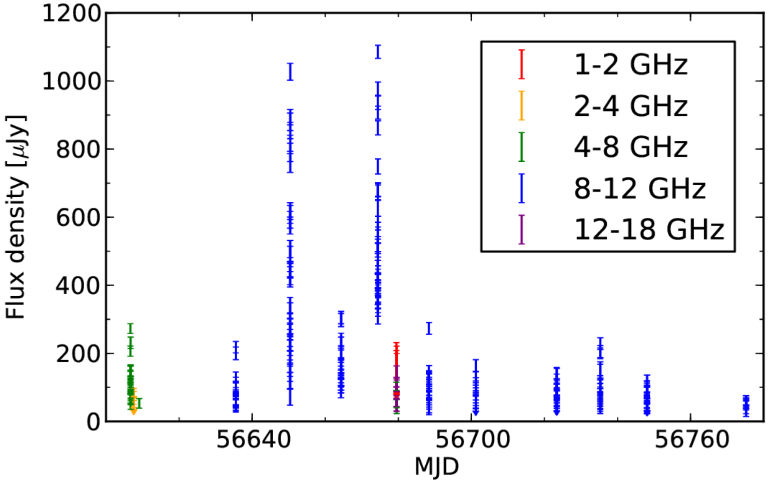




Intraday lightcurves

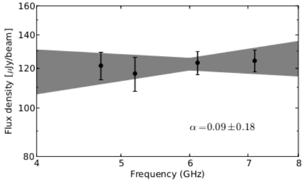


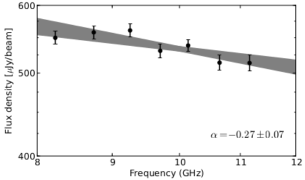
Long-term evolution (6 months)

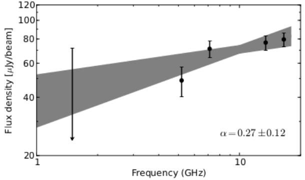


- In genral the flux density is $S_\nu \lesssim 100\ \mu$Jy
- Random rapid outburst up to $100 - 1000\ \mu$Jy

Radio spectral index







- Spectral index variability on timescales down to $\sim$5 min.
- In the range $-0.3 < \alpha < 0.3$
- No turnover could be detected below 4 GHz.

Additional results

- VLA
  - $T_{\rm B} > 3 \times 10^8$ K.
  - Polarization constrained to $< 4\%$ at 3σ.
  - Light-travel arguments $\Rightarrow$ size < 120 lt-s (30 orbit separation).
  - Maximum possible $T_{\rm B}$ of 10^{12} K $\Rightarrow$ size > 2 lt-s (0.5 orbit separation).

- e-EVN
  - Very faint compact source.
  - 50 ± 13 μJy/beam (3.8-σ) at the expected position

- LOFAR
  - Non-detection with a 3 σ upper limit of 5.4 mJy
  - Rules out scattered pulsar emission.

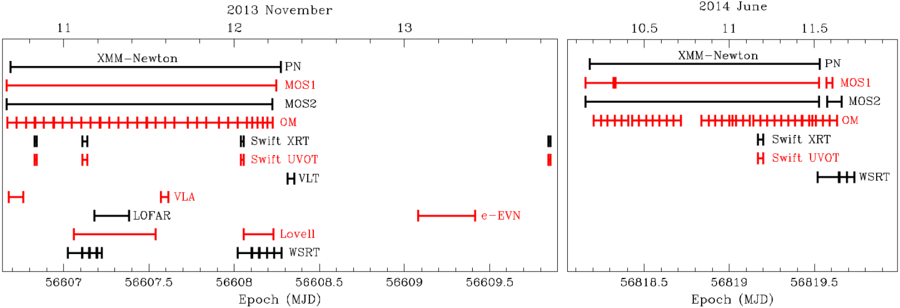
Summary of the radio monitoring

- J1023 is currently a highly variable radio source.
- Flat spectrum observed, expected from a compact outflow.
- No signature of the pulsar spectrum ($\alpha = -2.8$).
- Polarization non-detection can neither confirm nor rule out a partially self-absorbed jet.
- Radio emission comes from a region with size: $6 \times 10^{10} < \mathrm{s} < 4 \times 10^{12}$ cm

Multiwavelength campaign

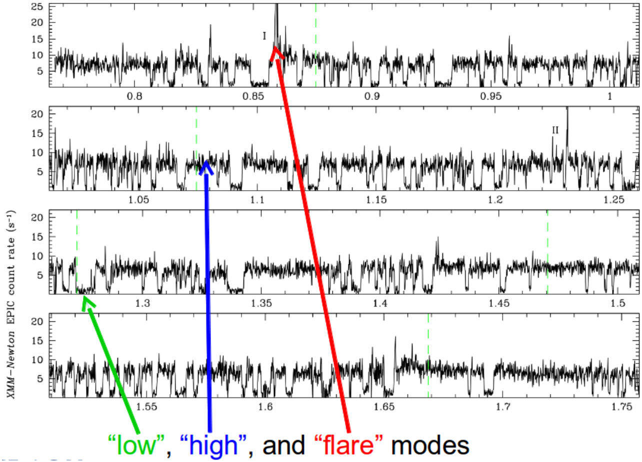
[Bogdanov, S., Archibald, A. M., Bassa, C., et al. A&A (in press), arXiv:1412.5145]

J1023 multiwavelength campaign



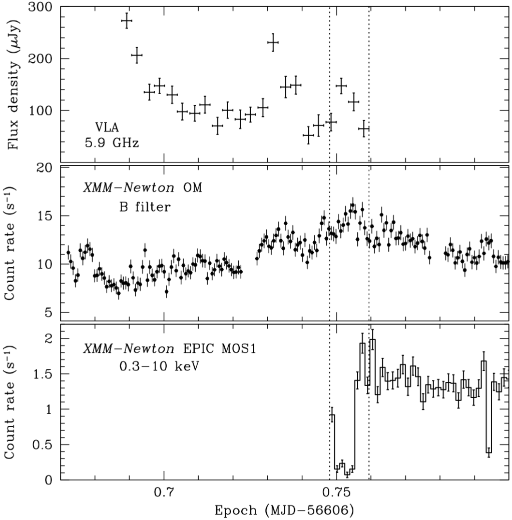
- Radio (+timing), optical, UV, X-rays. [Bogdanov et al. (in press)]

J1023 LMXB state: X-rays



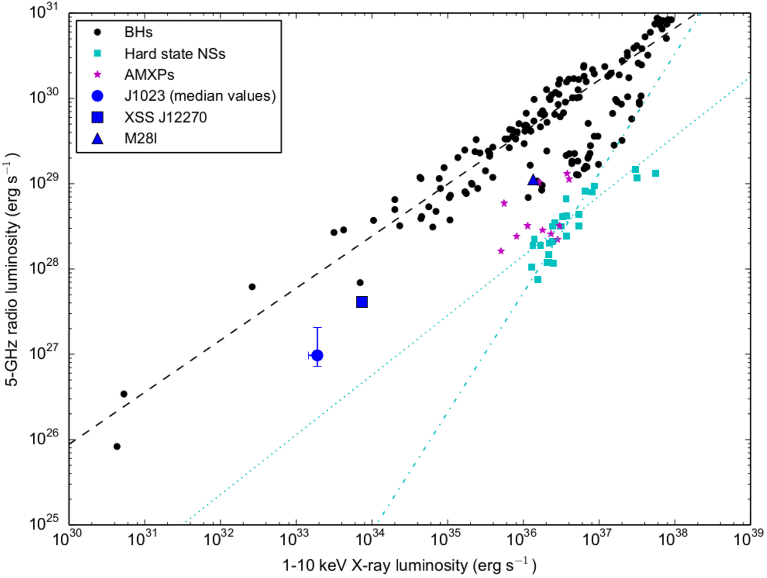
- Detection of X-ray pulsations in the high mode, at luminosities 100 times lower than other AMXPs. [Archibald et al. 2014]

Radio/X-ray correlation

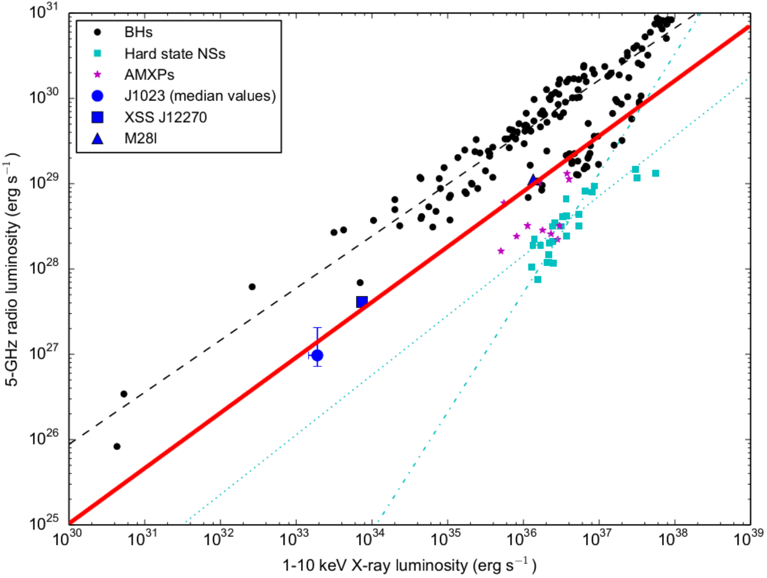


- Only 15 min of overlap between VLA and *XMM-Newton*.
- Given the long-term stability we compare the average VLA and *Swift* values.

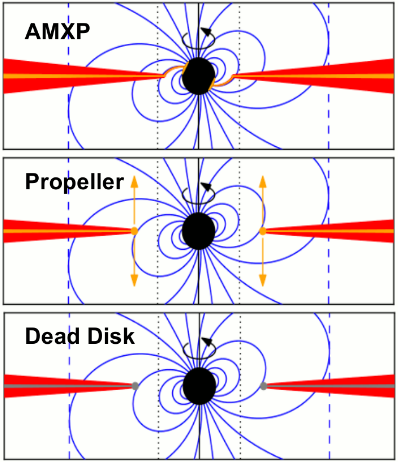
Radio/X-ray correlation



Radio/X-ray correlation

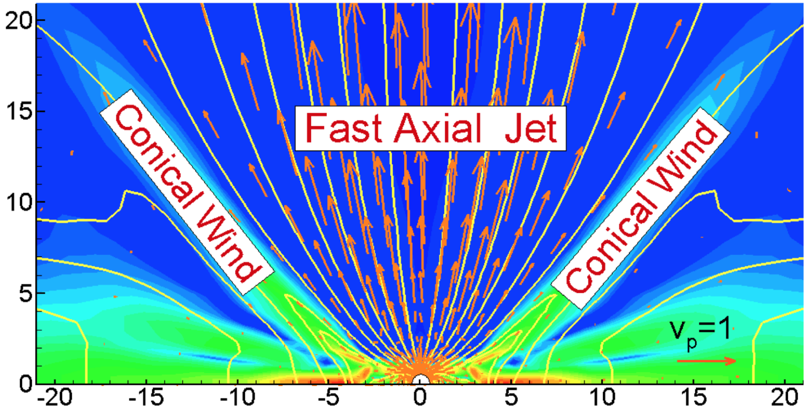


Physical mechanism?



- What mechanism operates to produce:
    - Acretion disk with wery underluminous X-ray emission.
    - X-ray pulsations. No radio pulsations.
    - Collimated outflow (flat spectrum).

Propeller mode in action



- MHD simulations of propeller-mode accretion [Romanova et al. 2009]
- More details in D. Torres talk and in [Papitto et al. 2015].

Propeller mode in action

- Propeller-style accretion fits the general view:
  - Material is expelled in high-velocity low-density outflows.
  - Naturally explains the transition to a jet-dominated regime at low accretion rates.
  - A small fraction of the material can reach the NS (X-ray pulsations).
  - Fermi acceleration at the turbulent, highly magnetized disk truncation region proposed as the mechanism accelerating gamma-ray-emitting electrons [Papitto et al. 2014, 2015].

- Change in spin frequency (after state change back to radio MSP) will help determine ratio of inflowing to outflowing material.

Conclusions

- Radio imaging detects highly variable but stable, flat-spectrum continuum radiation, consistent with an origin in a weak jet-like outflow.
- Pulsar mechanism appears to be quenched.

- Radio emission greatly exceeds extrapolations from NS LMXB systems at higher X-ray luminosities.
- We postulate that J1023 is undergoing radiatively inefficient propeller-mode accretion, with a jet-dominated accretion.

- The whole picture bears resemblance to the behavior predicted by a propeller disk accretion models.
- Change in spin frequency will be crucial.