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Discovery of a transitional Redback millisecond pulsar J1227-4853

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Neutron stars at the crossroads, 25th June 2015
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LMXB to MSP

- ✓ The extremely short spin period of millisecond pulsars are assumed to be outcome of accretion of the mass transferred by a low-mass (< Msun) companion star through an accretion disk.
- ✓ A Gyr-long mass accretion during which the system with an accretion disk appears luminous in X-ray; brighter in gamma-ray; radio continuum powered by outflow.
- ✓ 300 known radio MSPs in our Galaxy are believed to be recycled product of accreting neutron stars in low-mass X-ray binaries.
- ✓ Discovery of millisecond pulsation from accreting neutron stars in LMXB supports how mass accretion is able to effectively spin-up a neutron star.
- ✓ PSR J1023+0038 (Archibald et al. 2009) and J1824-2452I (Papitto et al. 2013) provide most convincing proof of evolutionary link shared by accreting neutron star in low-mass X-ray binary and radio millisecond pulsars.

Transitional MSP systems

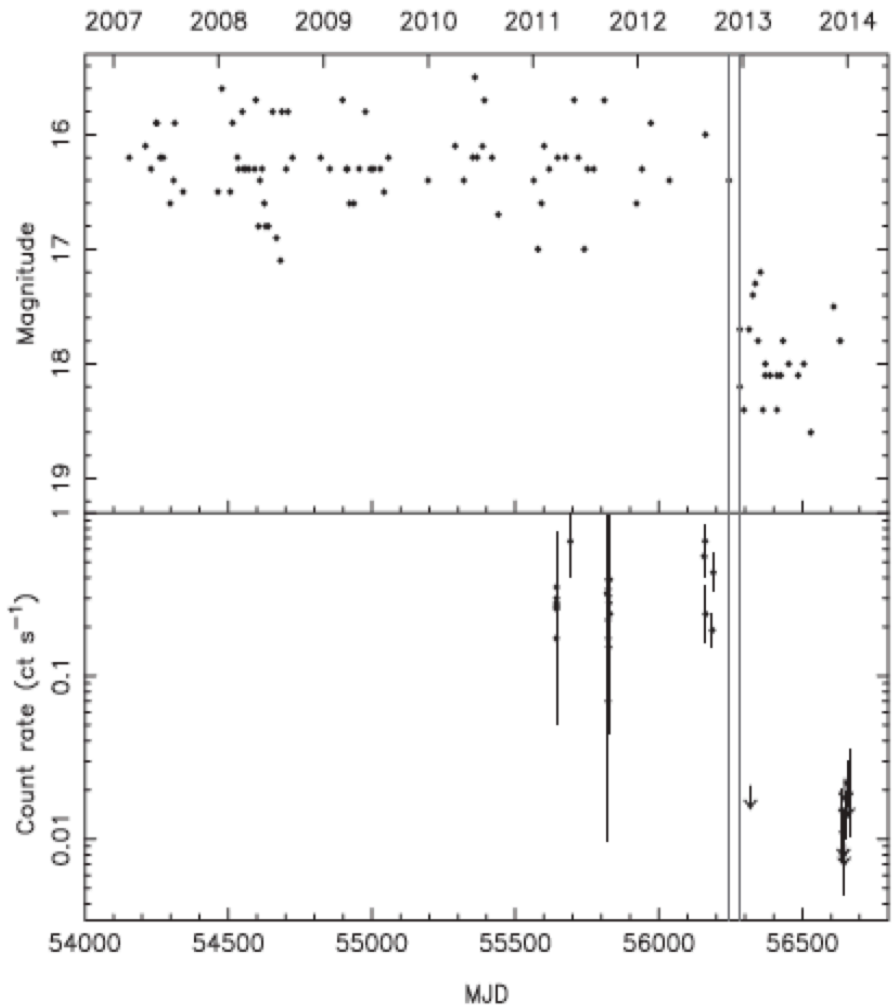
- ✓ PSR J1023+0038 with an evidence of accretion disk in 2000-2001; radio pulsar in 2009; reverse transition to LMXB in June 2013 (Stappers et al. 2014, Patruno et al. 2014) → decadal time-scale between transitions

- ✓ In last decade (2002-2013) IGR J18245-2452 has shown both rotation powered and accretion powered activities on a time-scales of few days to months. The short timescales observed for transitions between accretion-powered and rotation-powered states are comparable with those for typical X-ray luminosity variations, caused by swings of the mass inflow rate onto the neutron star.

- ✓ It is probable that a rotation-powered pulsar switches on during the X-ray quiescent states of other accreting millisecond pulsars

LMXB XSS J12270-4859

- ✓ A flat-spectrum radio emission possibility powered by outflow (Hill et al. 2011)
- ✓ X-ray, UV emissions compatible with accretion powered object (de Martino D. et al. 2013)
- ✓ Bassa et al. 2014 reported sudden decrease in X-ray and optical flux around November/December 2012
- ✓ Previous sign of accretion disk also disappeared
- ✓ XSS J12270-4859 may harbour an active rotation-powered MSP
- ✓ Orbital modulation of X-ray brightness (Bogdanov et al. 2014)



Courtesy : Bassa et al. 2014

The GMRT

- The Giant Metre-wave Radio Telescope (GMRT) is a radio interferometer operating at low radio frequencies (150, 244, 322, 607, 1060 to 1450 MHz)

- Array consisting of 30 antennas of 45 metres diameter, operating at metre wavelengths -- the largest in the world at these frequencies!

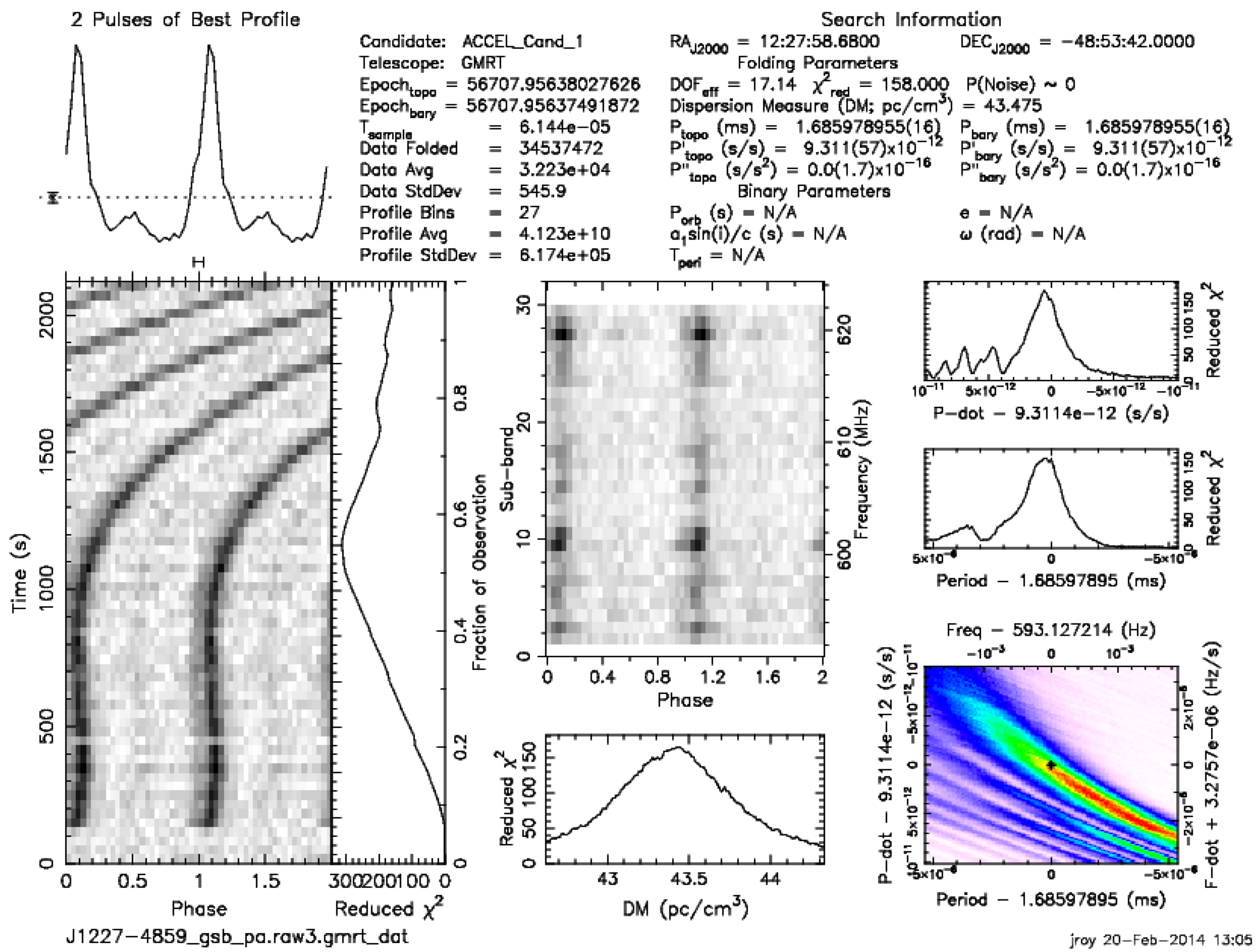
- Simultaneous dual beam search one with HPBW ~ 40' (incoherent with 0.4 mJy) other with 1' (coherent with 0.1 mJy)

- 2048 X 0.016 MHz spectrum @ 61 μs gives dispersion_smear < sample_resolution for DM up-to 100 pc cm^{-3}

- Synchronous time-domain and imaging study

Discovery of PSR J1227-4853

PSR J1227-4853, 1.69ms redback MSP at a DM of 43.5 pc cm^{-3} discovered at 607 MHz with the GMRT
(Roy, Bhattacharyya & Ray, Atel #5890, 2014)

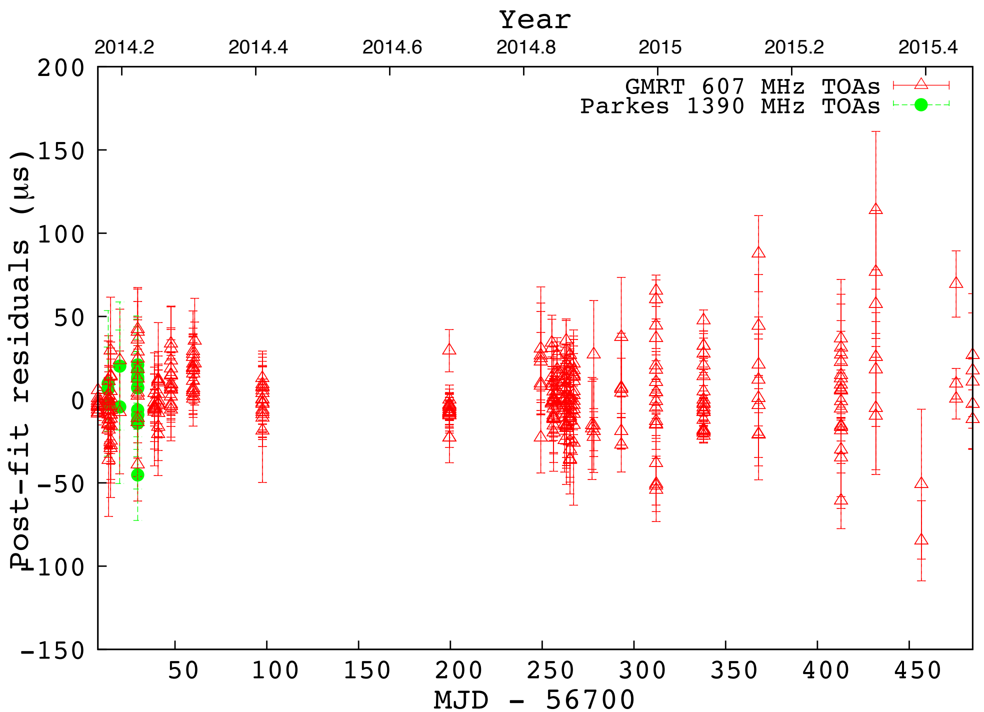


Timing of PSR J1227-4853

- ✓ 500 days of phase coherent timing combining GMRT-607 MHz and Parkes-1390 MHz TOAs resulting 15 μs residuals
- ✓ Model with four orbital period derivatives
- ✓ Companion mass of < 0.4 M_{sun}
- ✓ Edot/a^2 (4 x 10^{33} erg lt-s^{-2} s^{-1}): an order of magnitude higher than other MSP binaries

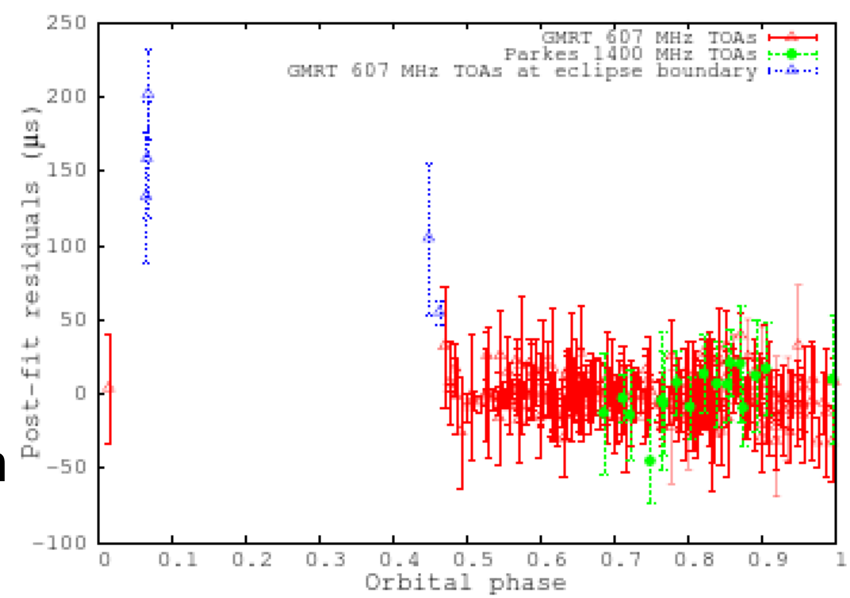
Parameter	Value[a]
2MASS position[b]	
Right ascension (J2000)	$12^h27^m58^s.748 \pm 0^s.06$
Declination (J2000)	$-48^\circ 53' 42''.88 \pm 1''$
Parameters from radio timing	
Right ascension (J2000)	$12^h27^m58^s.72130(8)$
Declination (J2000)	$-48^\circ 53' 42''.708(1)$
Pulsar frequency f (Hz)	592.9877736215(3)
Frequency derivative $\dot{f}$ (Hz s^{-1})	$-4.99\ (2) \times 10^{-15}$
Period Epoch (MJD)	56707.9764
Dispersion measure DM (cm^{-3} pc)	43.4235(7)
TEMPO binary model	BTX
Orbital frequency $FB0$ (Hz)	$4.02034494(7) \times 10^{-5}$
Orbital frequency first-derivative $FB1$	$5.3(2) \times 10^{-18}$
Orbital frequency second-derivative $FB2$	$-8.6(5) \times 10^{-25}$
Orbital frequency third-derivative $FB3$	$1.01(6) \times 10^{-31}$
Orbital frequency fourth-derivative $FB4$	$-5.1(3) \times 10^{-39}$
Projected semi-major axis x (lt-s)	0.668462(3)
Epoch of ascending node passage T_{ASC} (MJD)	56700.9070746(2)
Span of timing data (MJD)	56707.95–57184.54
Number of TOAs	477
Post-fit residual rms (μs)	15
Reduced chi-square	2.4
Derived parameters	
Mass function f ($M_\odot$)	0.0038696152
DM distance[c](kpc)	1.4
Flux density at 607 MHz[d](mJy)	6.6
Surface magnetic field B_s (10^8 G)	1.5
Spin down luminosity $\dot{E}$ (10^{35} erg s^{-1})	1.1
Characteristic age τ (Gyr)	2.4

Timing residuals

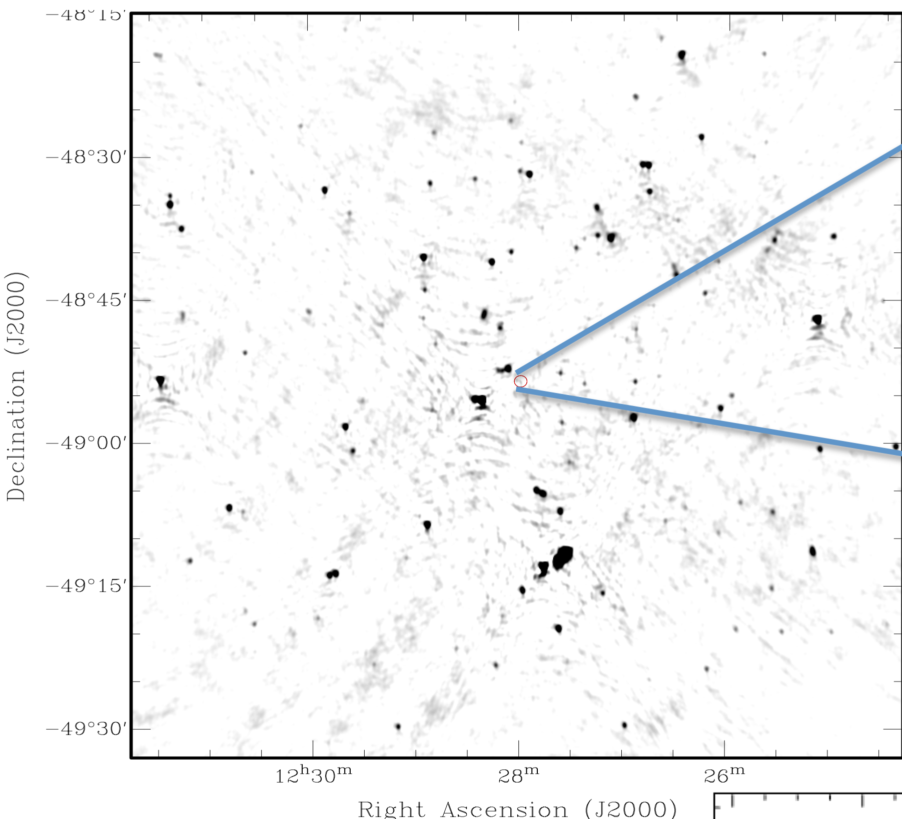


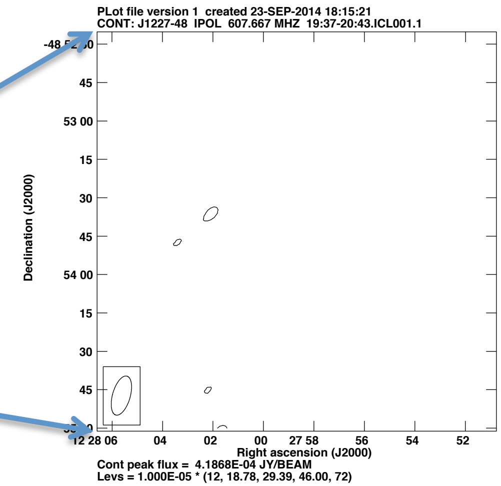
- ✓ ~ 322 TOAs from early 2014 to early June 2015
- ✓ A redback

- ✓ Roche lobe radius (0.24 R_{sun}) smaller than opaque part of companion orbit (4.9 R_{sun})
- ✓ Excess DM of 0.013 seen at eclipse egress → 4 x 10^{16} cm^{-2} added electron density

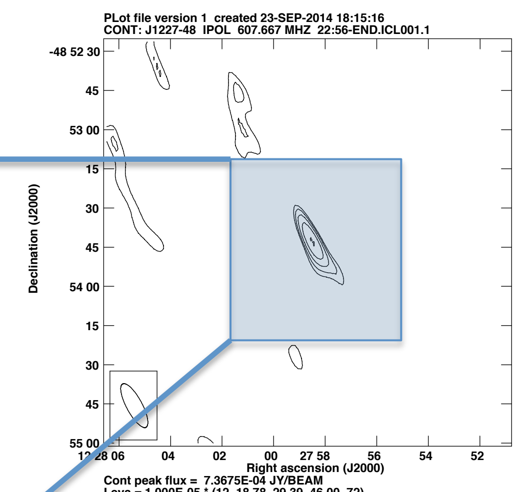


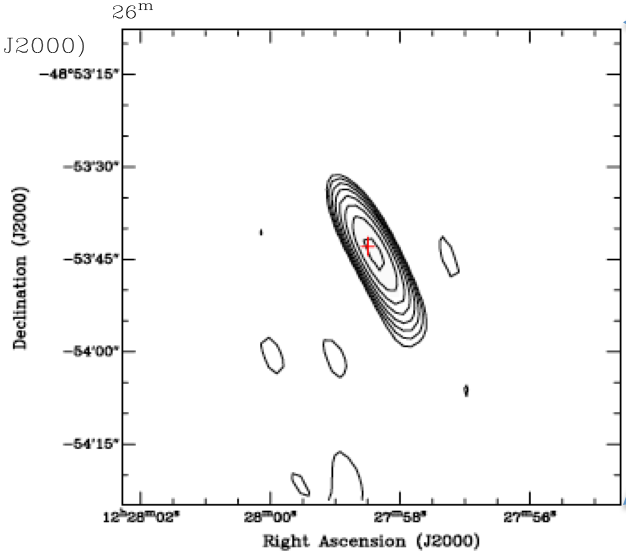
Synchronous radio imaging





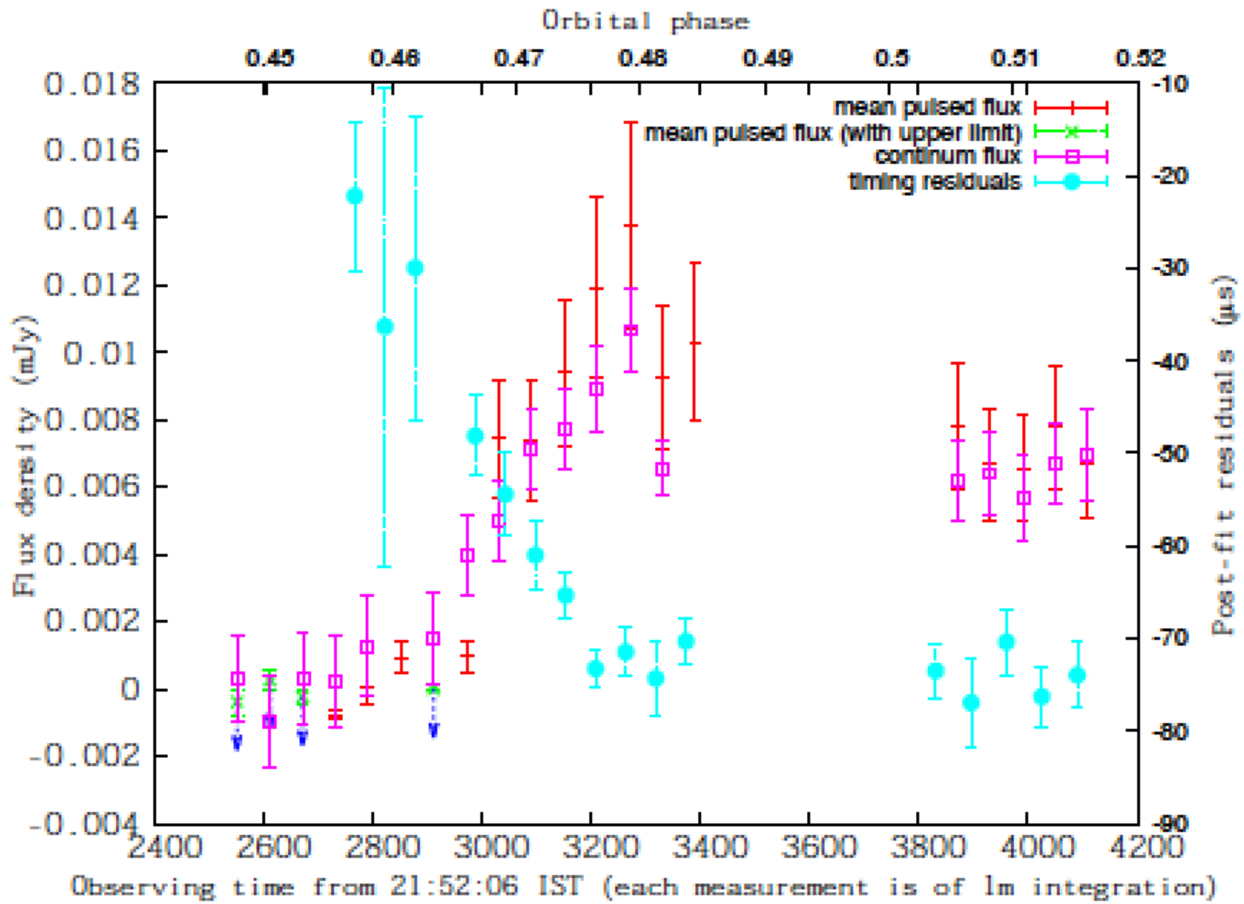
@ eclipsing binary phase





@ non-eclipsing binary phase

Continuum flux Vs pulsed flux



✓ Interstellar effects like scatter broadening or excess dispersion are not the cause of eclipse; probably absorption of radio waves are causing radio eclipse

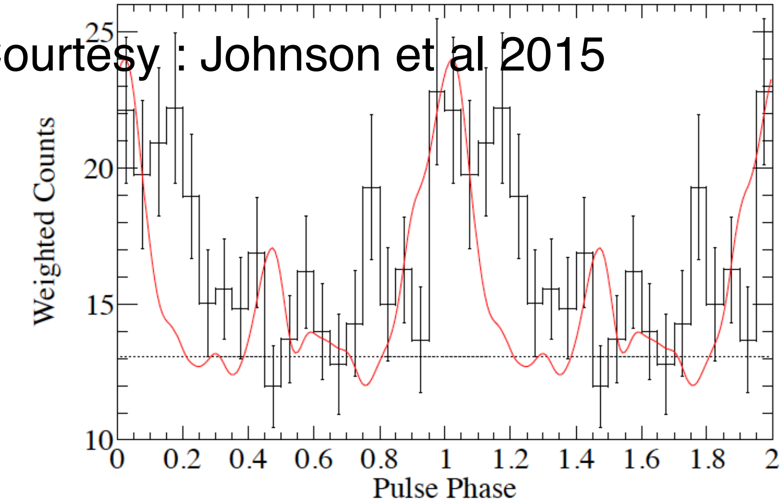
Pre-discovery radio observations

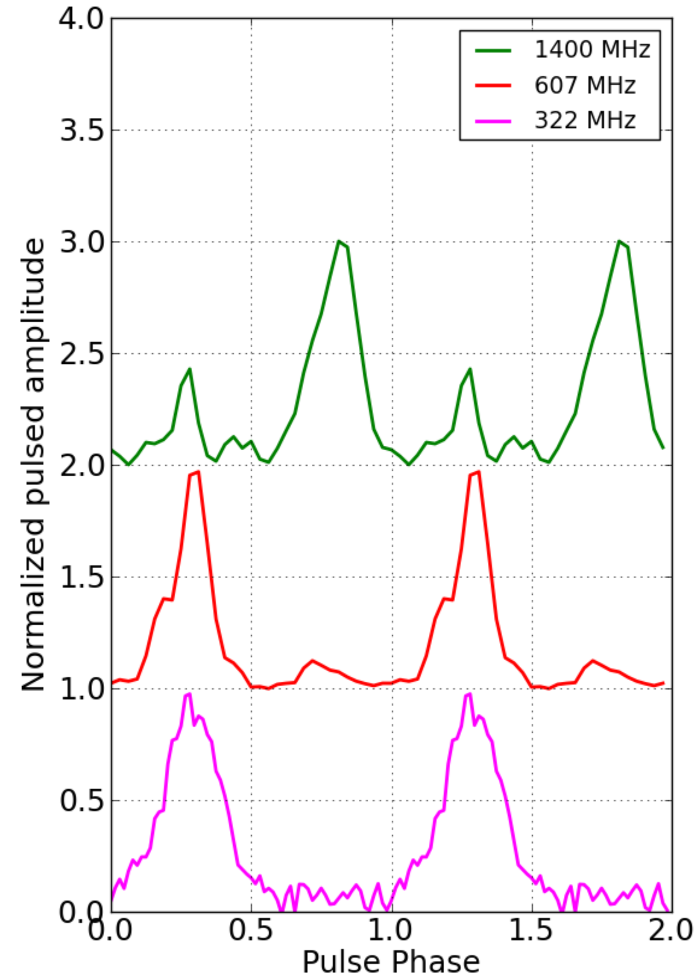
Telescope	Frequency (MHz)	Date	t_{obs} (h)	Orbital phase	S^a_{min} (mJy)	Reference
Parkes	1390	2009 Nov 25	2	0.12–0.41	0.15	Hill et al. (2011)
Parkes	1390	2010 Jul 18	1.1	0.05–0.21	0.20	Hill et al. (2011)
Parkes	1390	2010 Nov 12	1	0.25–0.40	0.21	Hill et al. (2011)
Parkes	1390	2012 Mar 22	1	0.78–0.92	0.21	Roy et al. (2015)[b]
GMRT	322	2012 Jul 23	1	0.88–0.02	0.09	Roy et al. (2015)[c]
Parkes	1390	2012 Nov 07	0.75	0.16–0.2	0.25	Roy et al. (2015)
Parkes	1390	2013 Nov 13	1	0.43–0.57	0.20	Bassa et al. (2014)
Parkes	1390	2013 Nov 13	1	0.58–0.72	0.20	Bassa et al. (2014)
Parkes	1390	2013 Nov 13	1	0.73–0.87	0.20	Bassa et al. (2014)
Parkes	1390	2013 Nov 13	1	0.87–0.02	0.20	Bassa et al. (2014)
Parkes	1390	2013 Nov 13	1	0.02–0.16	0.20	Bassa et al. (2014)
Parkes	1390	2013 Nov 17	1	0.48–0.62	0.20	Bassa et al. (2014)
Parkes	1390	2014 Jan 09	1	0.79–0.93	0.20	Bassa et al. (2014)

- ✓ Hill et al. 2009 observations shows radio emission powered by outflow
- ✓ Parkes 2012 Mar observations showed marginal detections
  → rotation powered pulsed emission active in LMXB-state (Takata et al 2014)!
- ✓ Parkes 2013 Nov 12 observations had few intermittent detections

Pulsed gamma-ray emission using Fermi-LAT

Courtesy : Johnson et al 2015





- ✓ > 6σ significance detections of gamma-ray pulsations using +6months data with same model as in Johnson et al 2015
- ✓ > 0.1 GeV light curve using data over the radio timing-span
- ✓ Gamma-ray peak nearly aligned with main peak of 1400 MHz radio profile
- ✓ Partial co-location of radio-gamma-ray emission region
- ✓ Considerable spectral evolution of two radio peaks

Gamma-ray emission

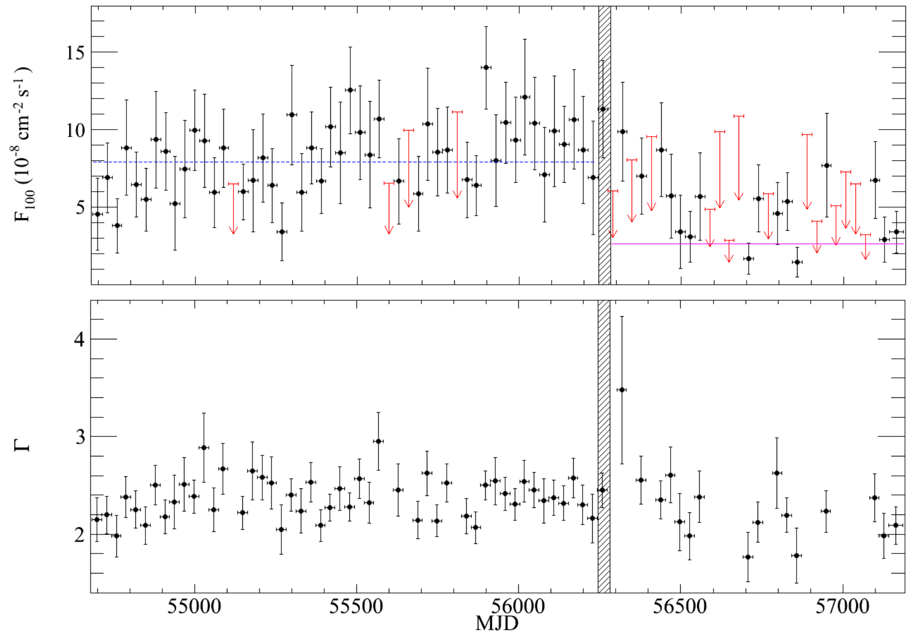
- ✓ Timing model with higher-order orbital period derivatives Vs Proper motion

- ✓ Photon flux dropped by 3x at transition

- ✓ Flux light curve with 2-day bins results the transition day as 2012 Nov 30

- ✓ Gradual decrease in gamma-ray flux at post-transition

- ✓ Propeller model to explain the gamma-ray and X-ray flux increase in LMXB-state (Papitto et al. 2014)



Courtesy to Tyrel Johnson

Summary

- ✓ Discovery of redback PSR J1227-4853 associated with LMXB XSS J12270-4859
- ✓ Signature of erratic binary orbital behavior
- ✓ Synchronous radio imaging to revel the eclipse cause
- ✓ Detection of post-transition gamma-ray pulsation from PSR J1227-4853
- ✓ Gamma-ray flux monitoring suggest probable transition day
- ✓ Significant profile evolution and gamma-ray emission model

Thank you!