Transitional Pulsars: MSP or LMXB? or The Redback Identity Crisis

(and other γ-ray pulsar stuff)

Tyrel Johnson
George Mason University
(resident @ US Naval Research Laboratory)

γ-ray Pulsars: A Brief Intro

Pulsars

Rapidly-rotating, highly-magnetized neutron stars.

$R_{NS} \sim 10$ km , $M_{NS} \sim 1 - 2\ M_{\odot}$, $B_{surf} \sim 10^{8}$-10^{15} G

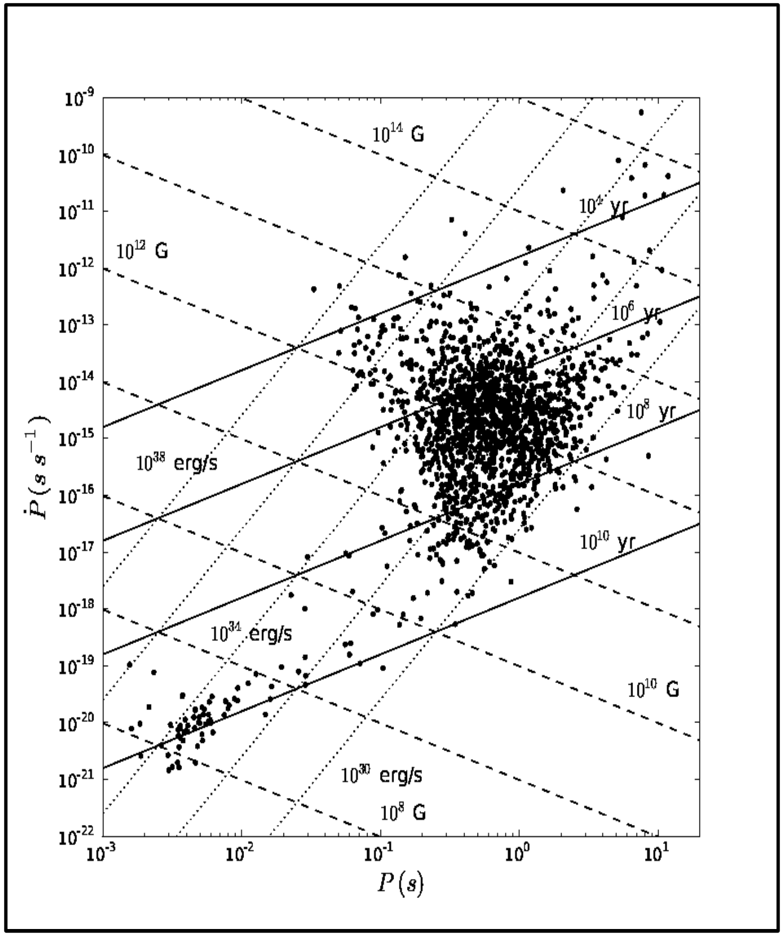
Spin periods (P) very stable

with the occasional glitch

Slowly increasing dP/dt > 0

Seen from radio to TeV γ-rays

(Focus on rotation-powered pulsars)



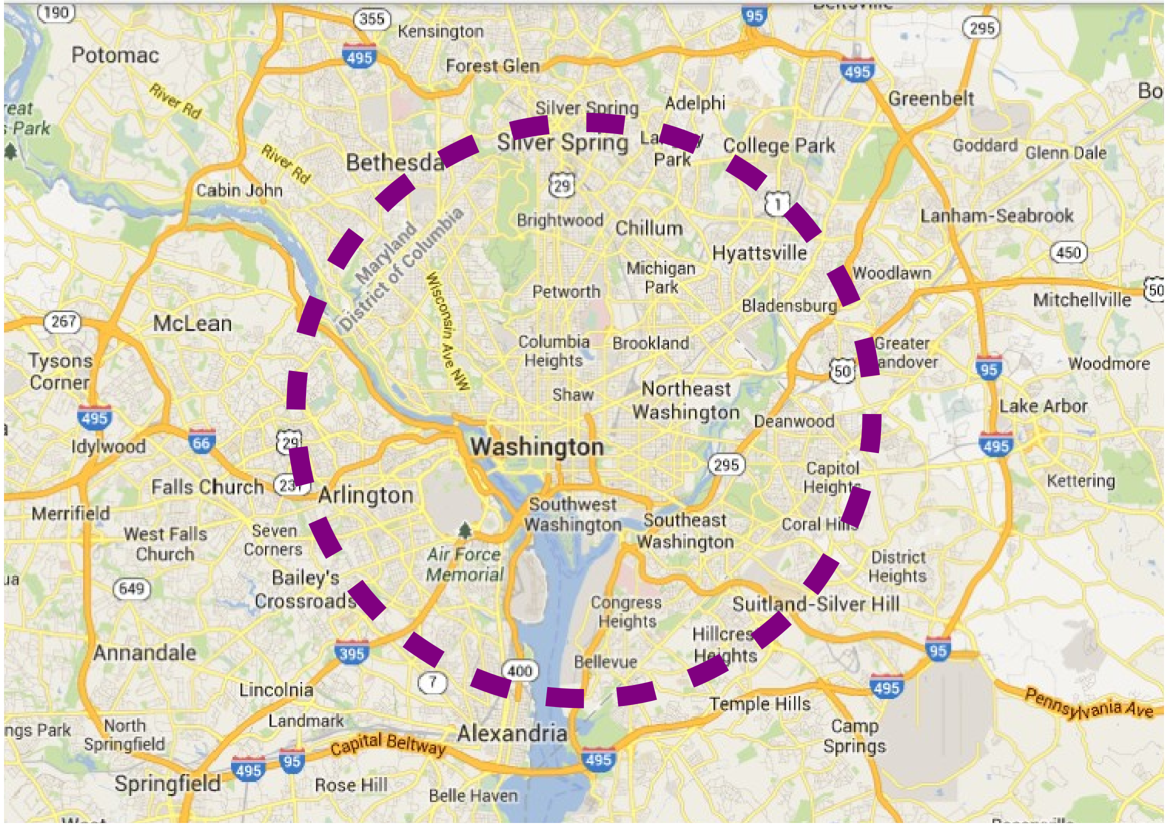
~2200 rotation-powered pulsars known

-radio, X-rays, γ-rays

ATNF pulsar databse v1.46

http://www.atnf.csiro.au/people/pulsar/psrcat/

Why? (I)


Potomac
Kensington
Forest Glen
Silver Spring
Adelphi
Greenbelt
Bethesda
Silver Spring
College Park
Goddard
Glenn Dale
Cabin John
Brightwood
Chillum
Lanham-Seabrook
Maryland
District of Columbia
Hyattsville
Michigan Park
Woodlawn
Petworth
Bladensburg
Mitchellville
McLean
Wisconsin Ave NW
Columbia Heights
Brookland
Greater Landover
Tysons Corner
Woodmore
Shaw
Northeast Washington
Lake Arbor
Idylwood
Deanwood
Washington
Capitol Heights
Kettering
Falls Church
Arlington
Merrifield
Southwest Washington
Southeast Washington
Coral Hills
West Falls Church
Seven Corners
Air Force Memorial
District Heights
Bailey's Crossroads
Congress Heights
Suitland-Silver Hill
Hillcrest Heights
Annandale
Bellevue
Lincolnia
Temple Hills
Landmark
Alexandria
Camp Springs
North Springfield
Capital Beltway
Pennsylvania Ave
Springfield
Rose Hill
Belle Haven
River Rd
Cabin John
190
355
95
295
495
29
1
450
267
66
50
231
649
395
7
400

Why? (II)

Magnetic fields and density we can't reproduce on Earth

- Extreme systems
- Allows observations of processes (e.g., one-photon pair production) can't see in laboratories

Born in supernova explosions, one endpoint of stellar evolution

- What is the equation of state at these densities?
- Strange matter? Quark stars?

Most stringent test of general relativity to date

- Test strong gravity
- Pulsar timing arrays to detect gravitational waves

Pulsar navigation

- Use known X-ray millisecond pulsars (MSPs) as reference points

Pulsed Light Curves

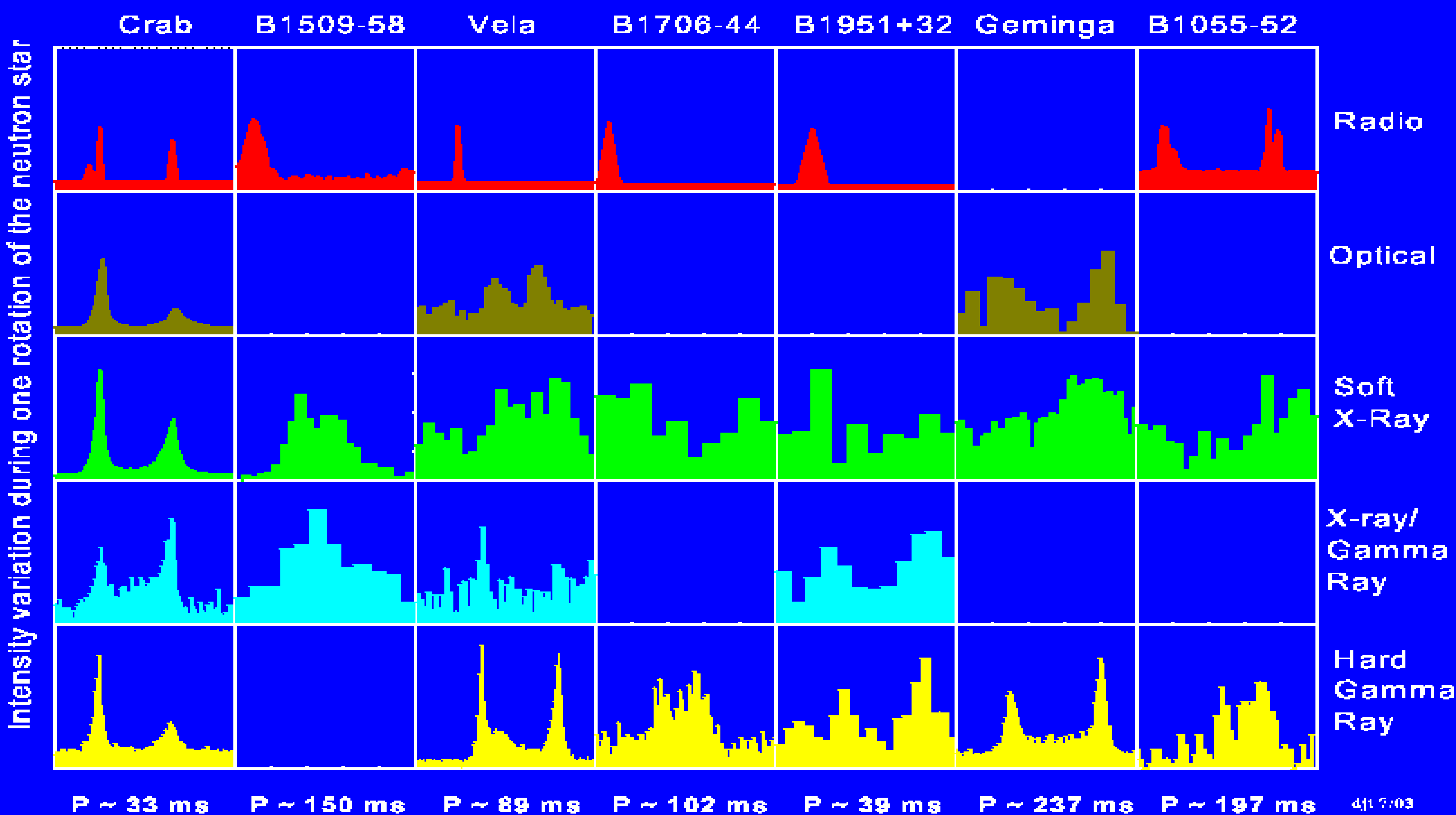


Figure courtesy D. J. Thompson

Pulsar SEDs

Crab pulsar ≥50 MeV pulsations
Browning+ (1971), balloon experiment.

SAS-2 satellite detects pulsed gamma rays from the Vela pulsar (Thompson+ 1975).

Compton Gamma-Ray Observatory
EGRET saw 6 pulsars ≥100 MeV
1 pulsar only at lower energies by OSSE and COMPTEL.

- Emission "cutoff" ~few GeV couldn't characterize cutoff
- no significant variability
- γ-rays lag radio by ≥ 0 phase shift (if seen)

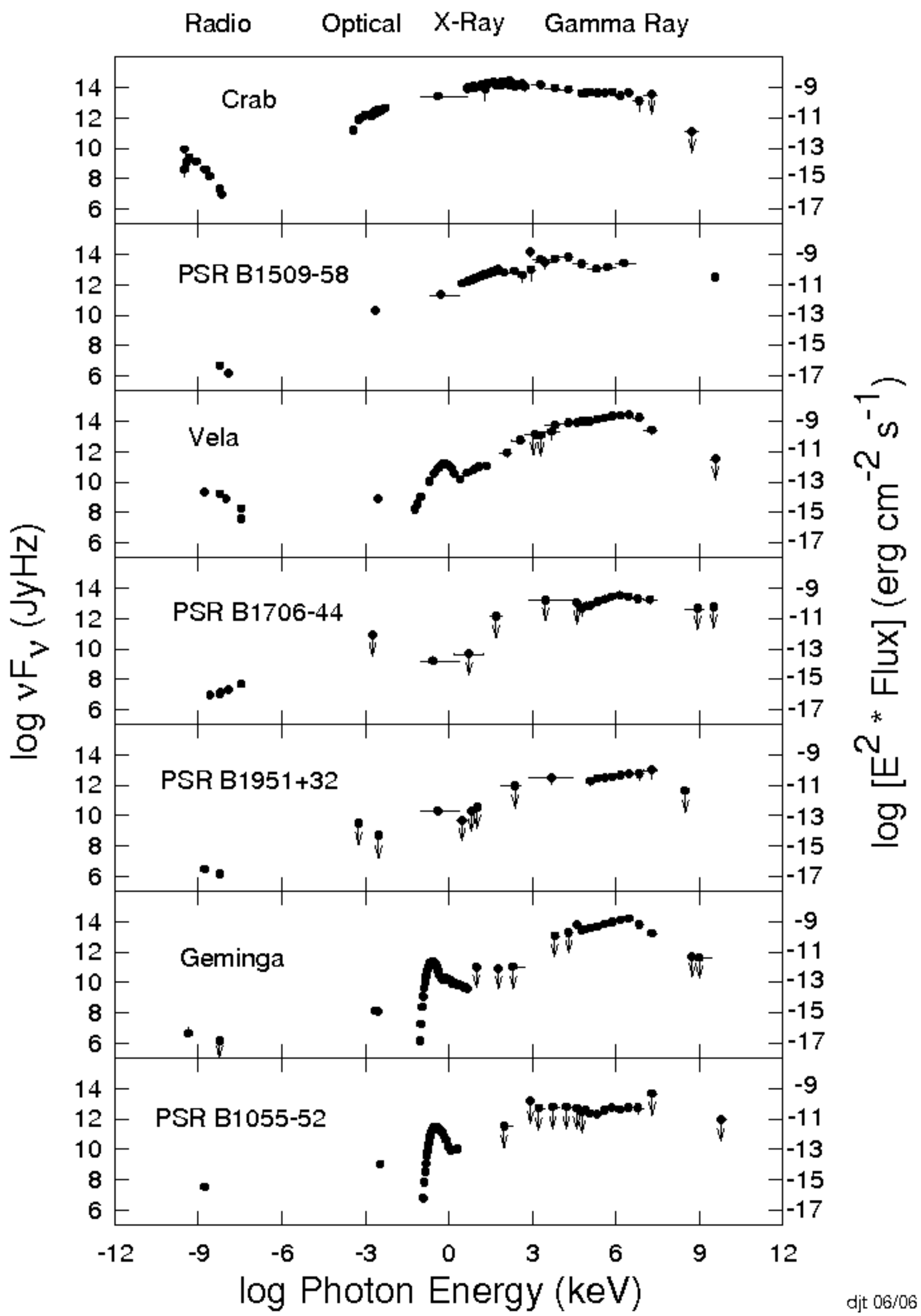


Figure courtesy D. J. Thompson

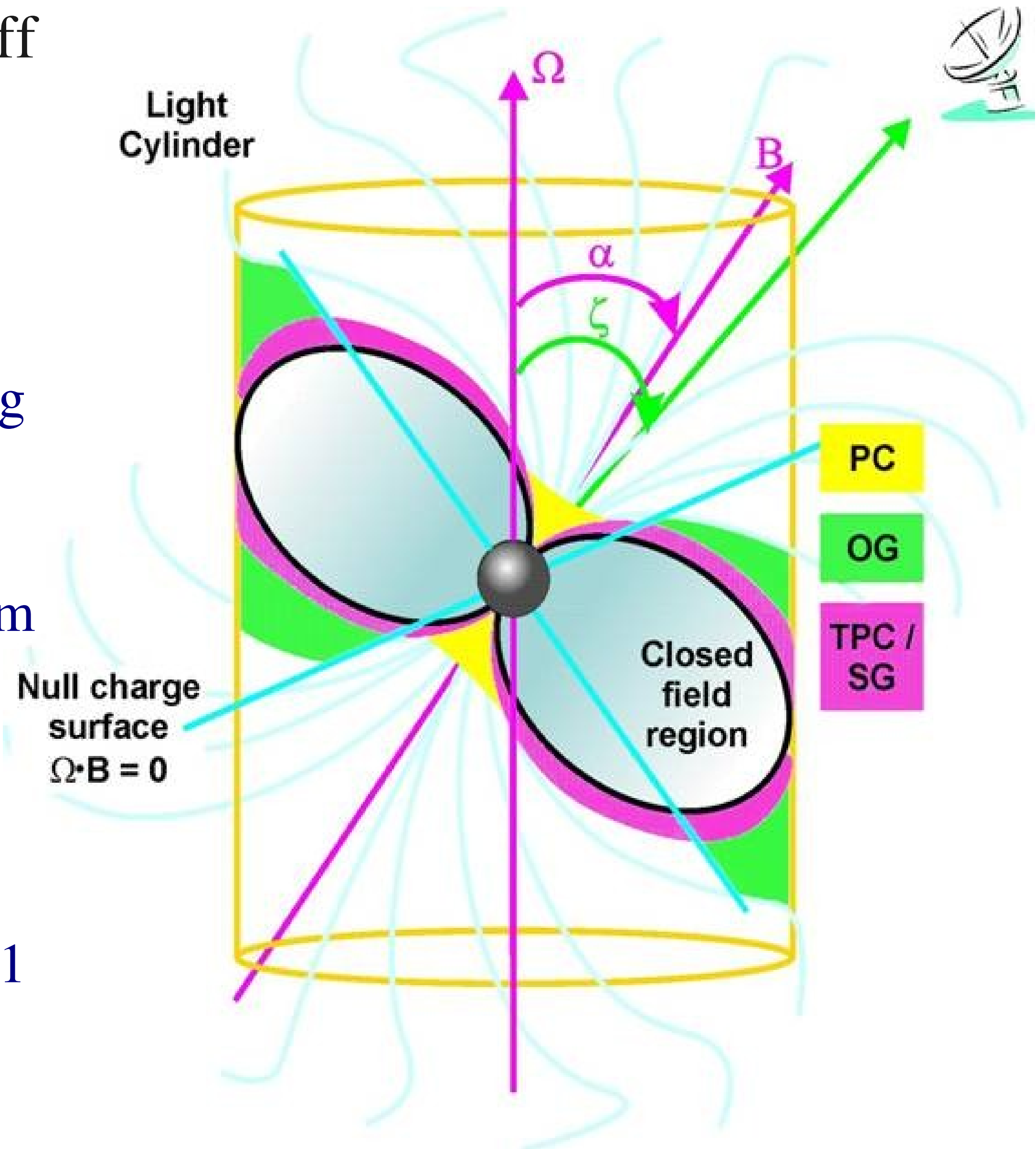
Gamma-ray Emission

Curvature radiation, exponentially-cutoff power-law spectrum, non-variable

Polar cap – emission from just above the surface, strong B-field, one-photon pair production, b>1 (e.g., Daugherty & Harding 1996)

Slot gap/two-pole caustic – emission from surface to light cylinder in narrow vacuum gap, b=1 (e.g., Dyks & Rudak 2003;Muslimov & Harding 2004)

Outer gap – emission above NCS only, b=1 (e.g., Cheng+ 1986; Romani 1996)



The Emission is Out There

Vela Pulsar:
Calibration pointing-mode and early sky-survey data

E_C = 2.86±0.09 GeV
Γ = 1.51±0.01

b = 2 excluded at 16.5σ

More pulsars detected, similar result…near-surface emission ruled out as dominant gamma-ray emission site.

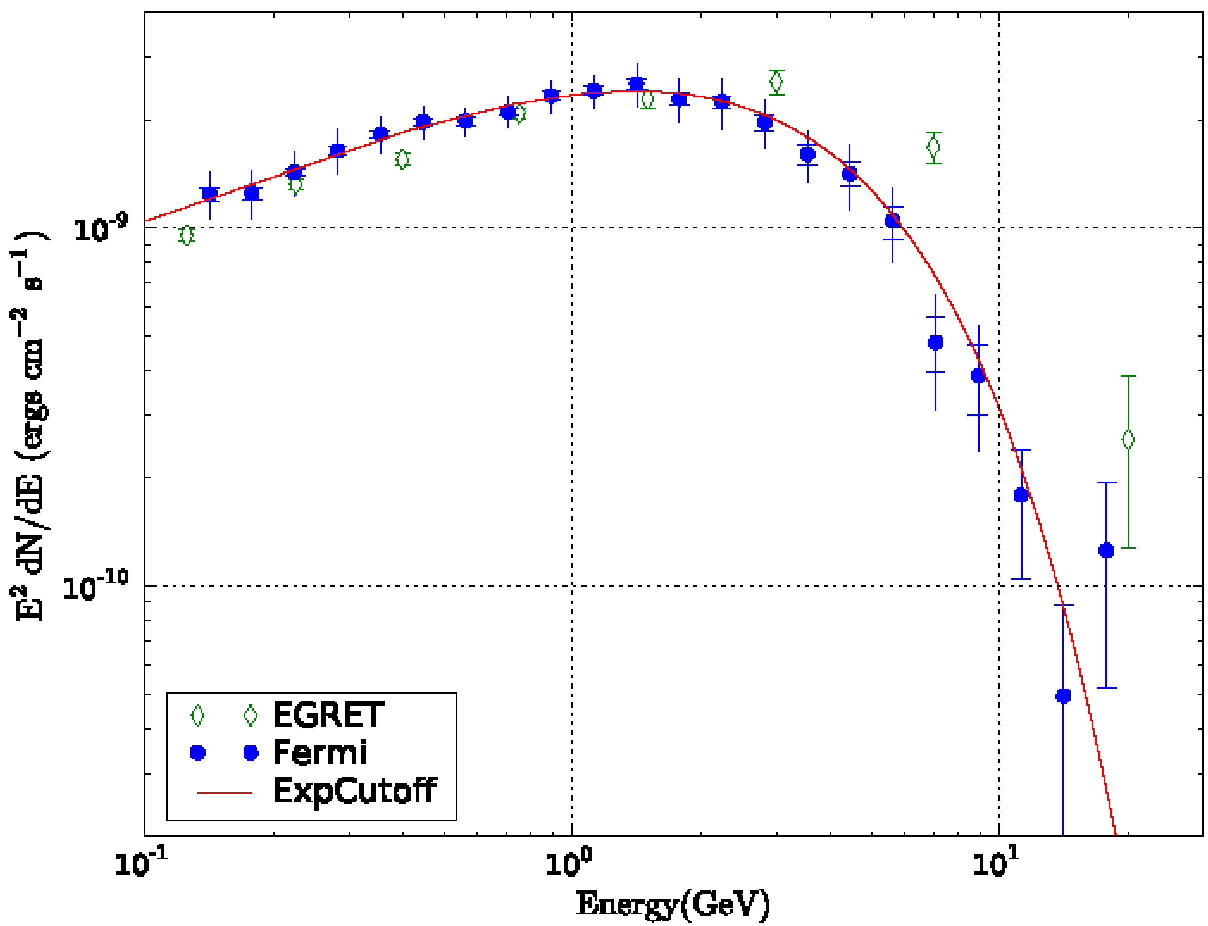
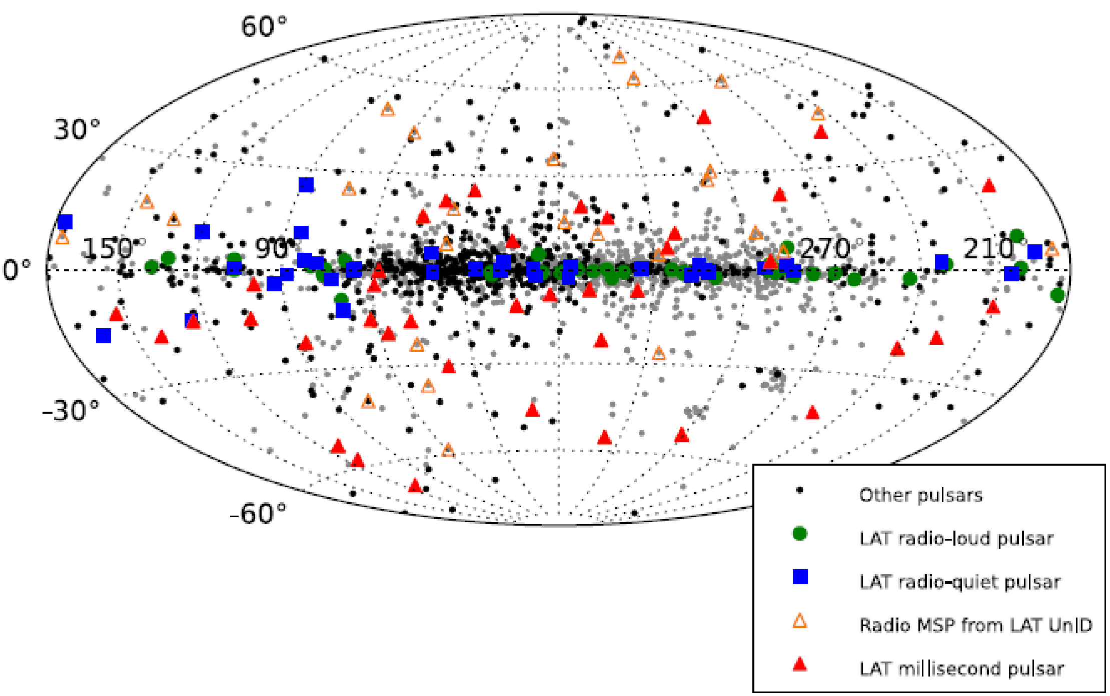
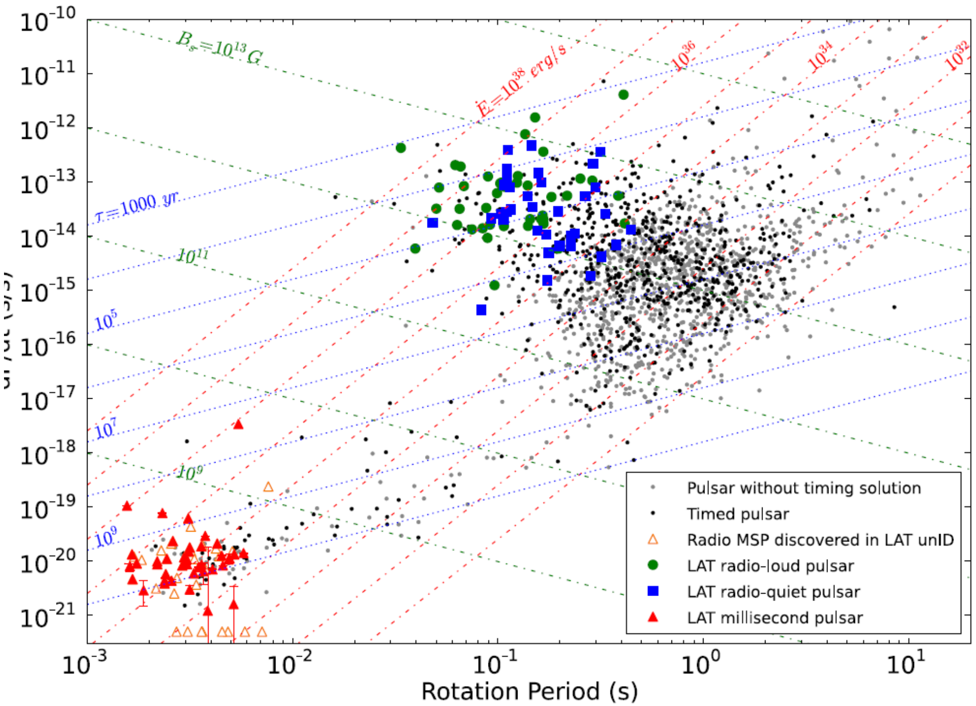


Fig. 5 Abdo+ (2009)

The Second LAT Pulsar Catalog

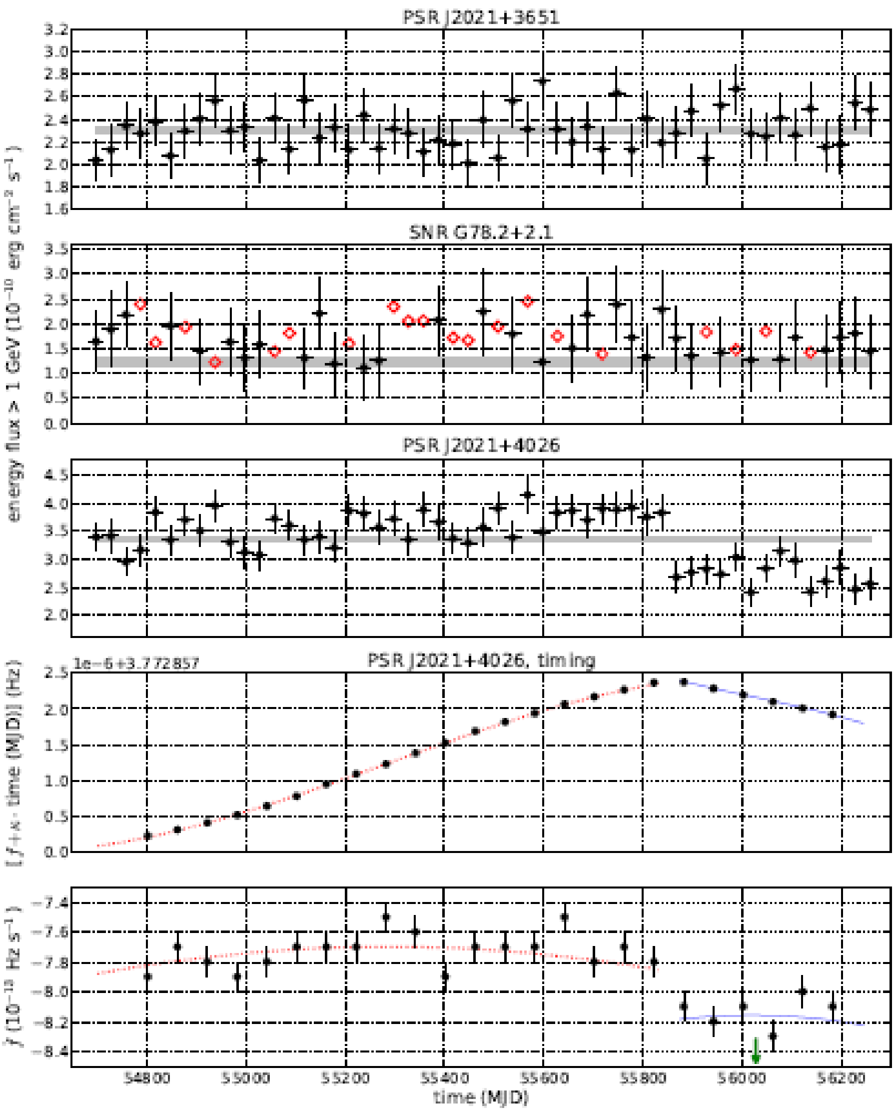
Abdo+ 2013, ApJS, 208, 17; auxiliary files at
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/

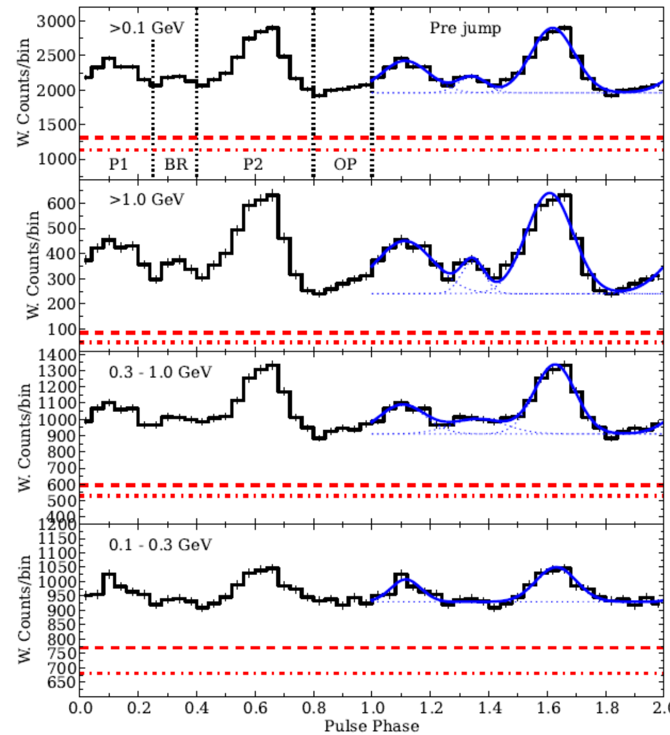


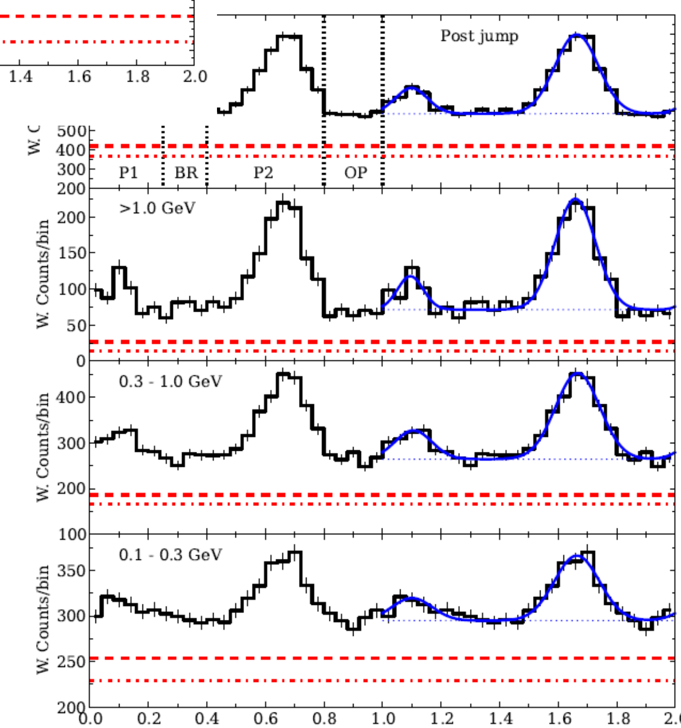


Category	Count	Sub-count	Fraction
Gamma-ray pulsars in this catalog	117		
Young or middle-aged		77	
Radio-loud gamma-ray[b]		42	36%
Radio-quiet gamma-ray		35	30%
Gamma-ray MSPs (isolated + binary)		(10+30) = 40	34%

A Variable Pulsar!?!?







Allafort+ (2013)

Pulsars at TeV Energies!?!?

Fig. 1 Aliu+ (2011)

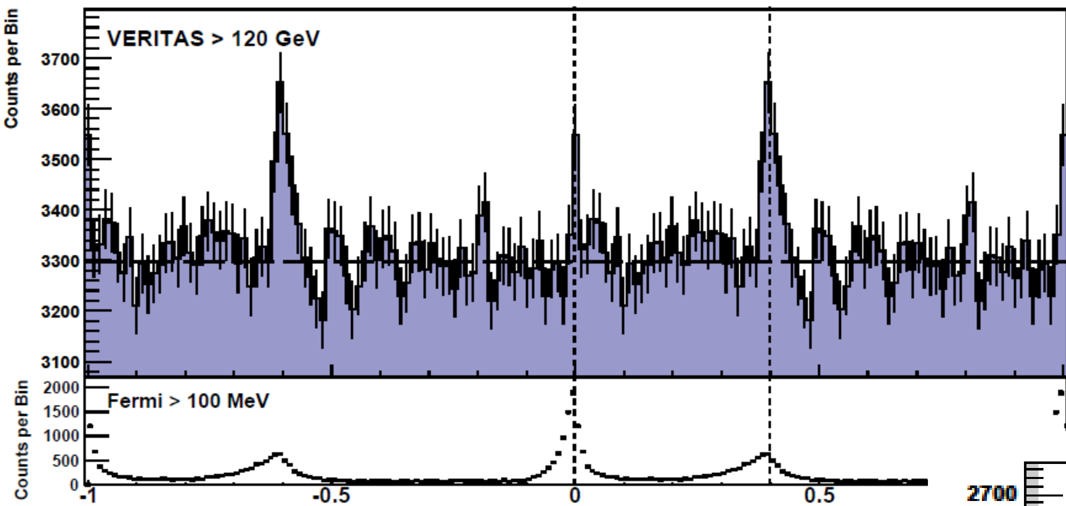
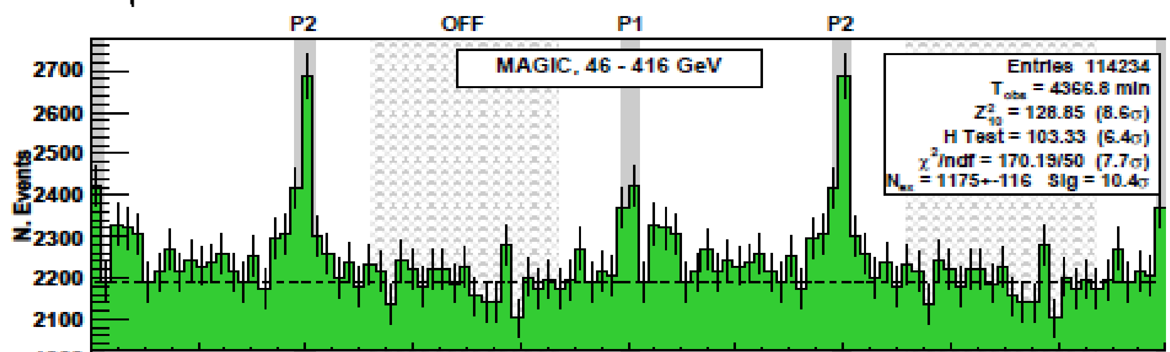
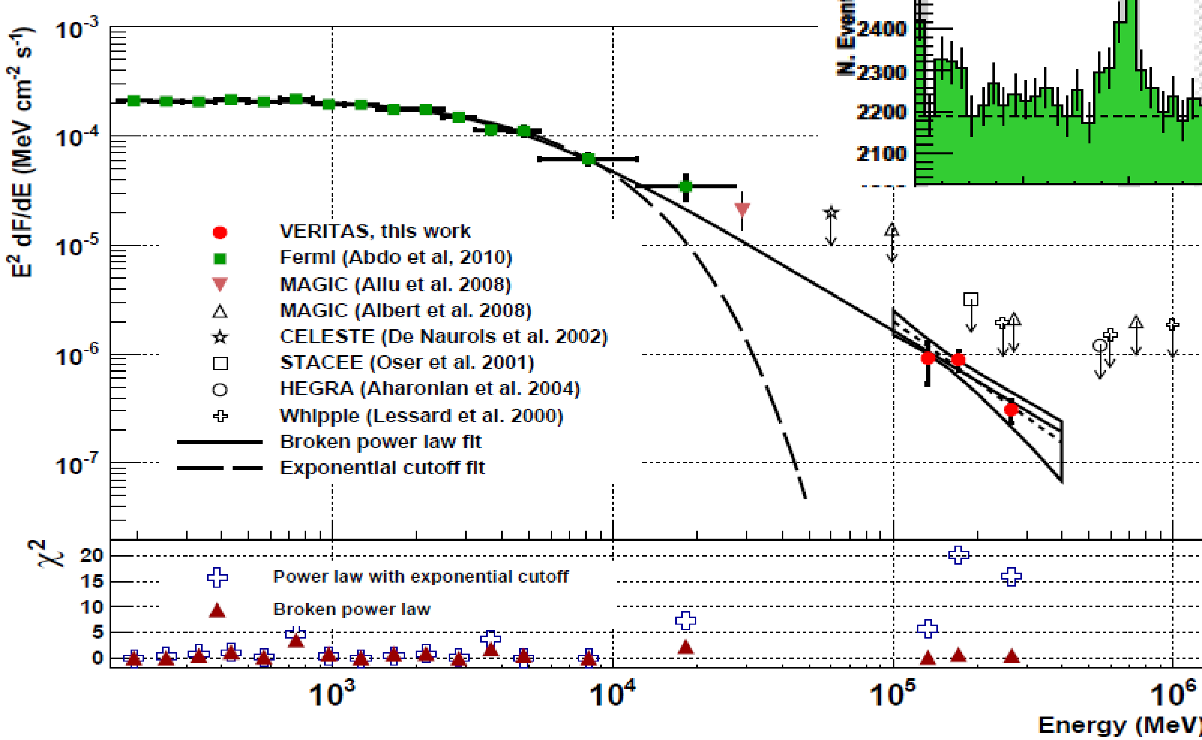


Fig. 1 Aleksic+ (2012)

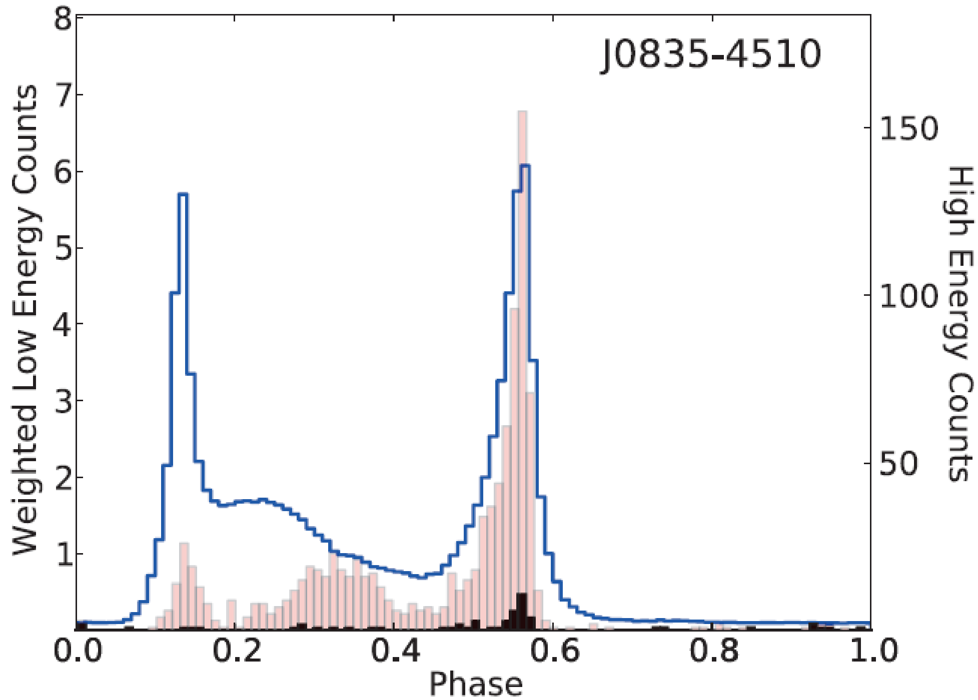


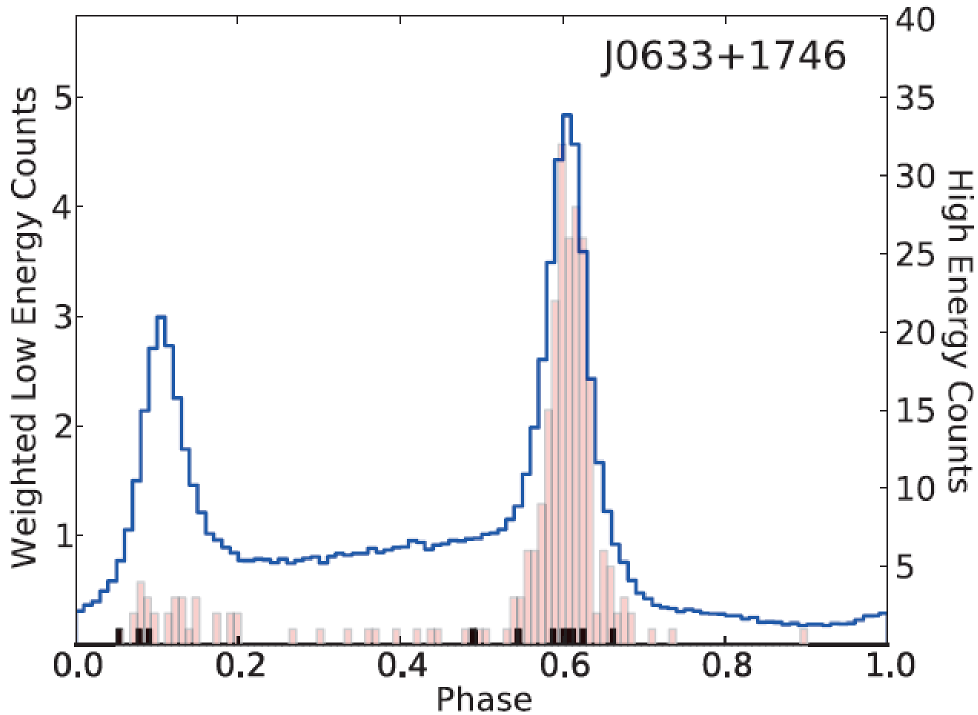


Hard Pulsars

Difficult to predict what TeV telescopes will see using LAT 1FHL catalog (Ackermann et al. 2013, ApJS, 209, 34), 3 years, ≥10 GeV

- Associations with 27 pulsars
- ≥10 GeV pulsations from >20





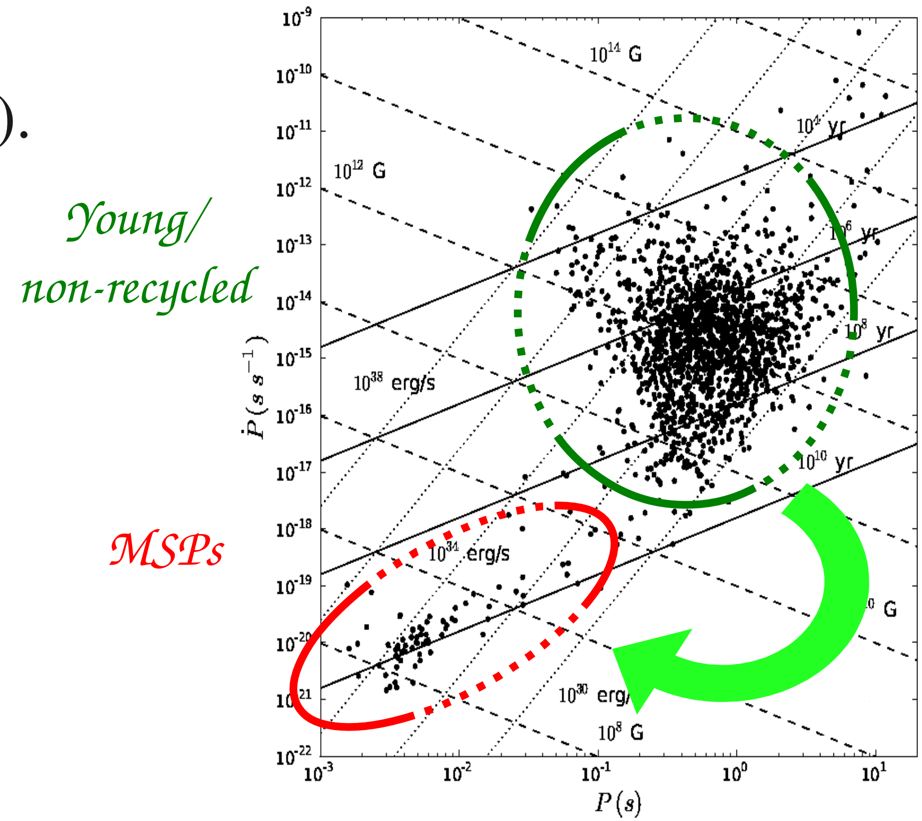
Millisecond Pulsars

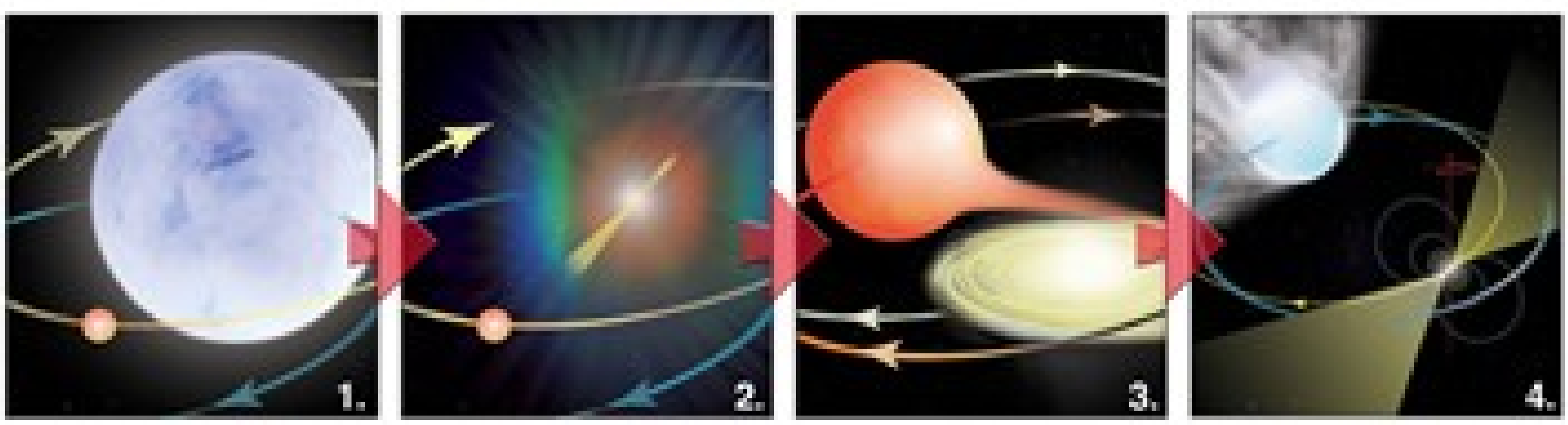
Pulsars Are Green

1st MSP discovered by Backer et al. (1982).

Recycled pulsars (e.g., Alpar et al., 1982):

- "Normal" pulsar in a binary system
- Spins down, ~> 10^6 yr
  - move down and left on P-Pdot plot
  - how to get to lower left corner?
- Spun up by accretion





Previous Observational Evidence

>80% of MSPs in binary systems

- Isolated MSPs result of binary disruption of companion evaporation

Many MSPs in globular clusters

- Old systems, high chance of forming binaries

Discovery of accretion-powered, ms pulsations in some LMXBs

- e.g., Wijnands & van der Klis 1998

PSR J1023+0038: missing link MSP and first “redback”

- Discovered as rotation-powered radio MSP in 2009
- Evidence for accretion disk in 2000-2001

γ-ray Spiders

"Black Widows" (BWs) and "Redbacks" (RBs)

- MSPs in binaries with low-mass companions (~0.02$M_\odot$, BW; ~0.2$M_\odot$, RB)
- Short orbital periods (<1day)
- Companions ablated by pulsar winds
- 3 BWs and 1 RB pre-*Fermi* (not in globular clusters)
  - At least 16 BWs and 9 RBs post-*Fermi*

Redbacks in more detail

- Radio eclipses
- Non-degenerate companions
- Orbitally modulated X-ray emission
  - Shock emission, between winds of the pulsar and its companion
  - Studies of PSR J1023+0038 suggest shock is close to companion
  - As yet, no conclusive orbital modulation in γ-rays
- "MSP near the end of, but maybe not totally done with, the recycling phase"
  - See Roberts+ (arXiv:1402.5507) for a review

Transitional Pulsars

M28I Caught in the Act!

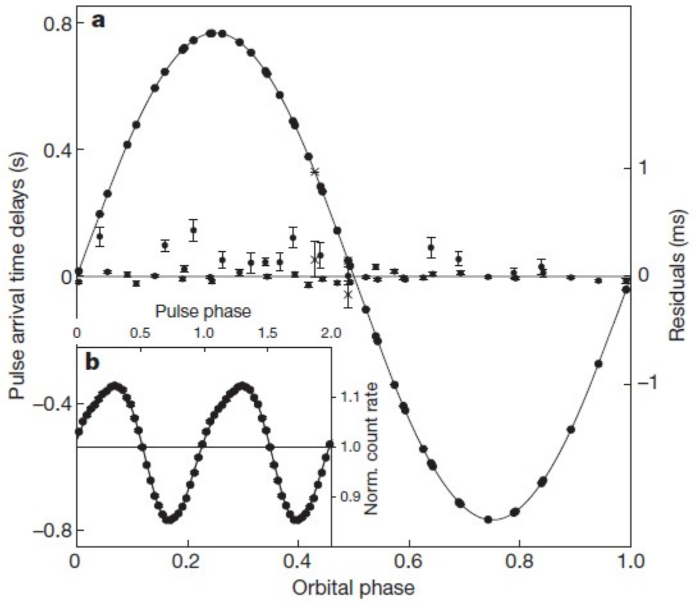
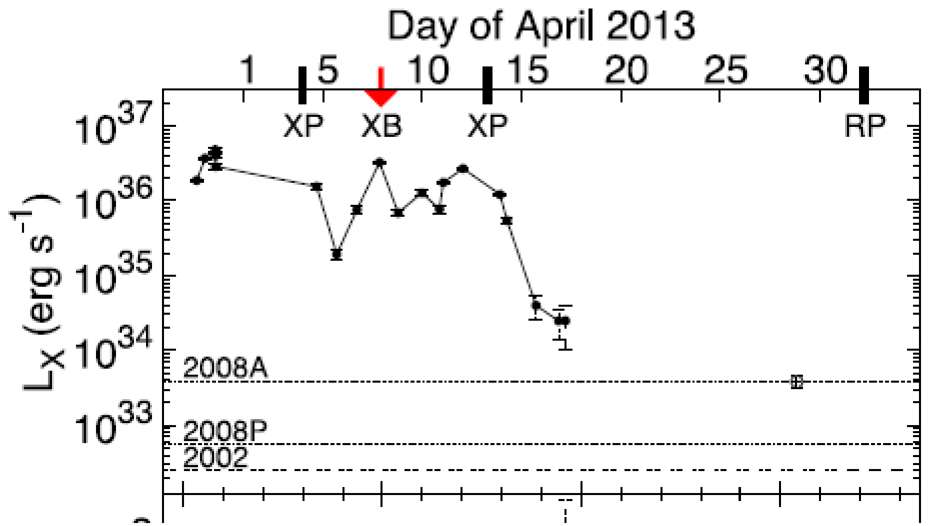


Figure 2 | Spin and orbit of IGR J18245−2452. a, Delays in pulse arrival time

Papitto+ 2013



Linares+ 2014

Table 1 | Spin and orbital parameters of IGR J18245−2452 and PSR J1824−2452I

Parameter	IGR J18245−2452	PSR J1824−2452I
Right ascension (J2000)	18 h 24 min 32.53(4) s	
Declination (J2000)	−24° 52′ 08.6(6)″	
Reference epoch (MJD)	56386.0	
Spin period (ms)	3.931852642(2)	3.93185(1)
Spin period derivative	$< 1.3 \times 10^{-17}$	
Root mean square of pulse time delays (ms)	0.1	
Orbital period (h)	11.025781(2)	11.0258(2)
Projected semimajor axis (light-seconds)	0.76591(1)	0.7658(1)
Epoch of zero mean anomaly (modified Julian date)	56395.216893(1)	
Eccentricity	$\leq 10^{-4}$	
Pulsar mass function ($M_\odot$)	$2.2831(1) \times 10^{-3}$	$2.282(1) \times 10^{-3}$
Minimum companion mass ($M_\odot$)	0.174(3)	0.17(1)
Median companion mass ($M_\odot$)	0.204(3)	0.20(1)

PSR J1023+0038 Changes Back

The Astrophysical Journal, 790:39 (8pp), 2014 July 20 Stappers et al.

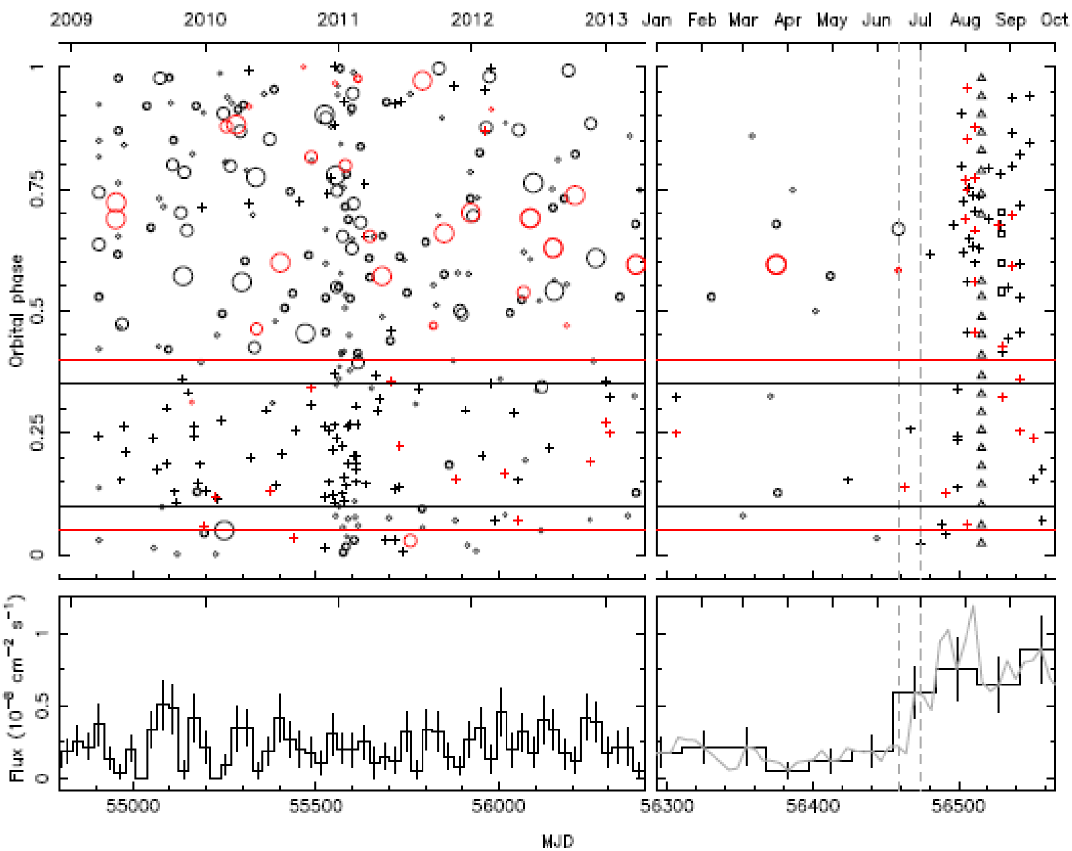


Figure 1. Timeline for the state change in J1023. Top panel: radio observations of J1023 with the LT at 1500 MHz and WSRT at 1380 MHz (black symbols), WSRT at 350 MHz (red symbols), GBT at 2 GHz (triangles) and Arecibo at 4.5 GHz (squares). The observations are plotted against time and orbital phase, where an orbital phase of zero has the pulsar passing the ascending node. The left panel shows data from 2009 to 2013, while the right panel shows the data from 2013. Observations where the pulsar was not detected are denoted by pluses, triangles and squares, while detections are shown by circles, with the circle size indicating the signal-to-noise of the detection. The horizontal lines show the average eclipse duration at 1380 and 1500 MHz (black) and 350 MHz (red). The vertical dashed lines indicate the last confirmed detection on 2013 June 15 of the pulsed signal and the first non-detection outside the known eclipse region on 2013 June 30. Bottom panel: 1–300 GeV γ-ray photon flux computed with aperture photometry. The steps (solid line) show the flux averaged over 2.5 Ms segments, with Poisson errors. The gray line shows the result of taking the same 2.5 Ms averages with intermediate starting points, effectively convolving the photon arrival time series with a 2.5 Ms top-hat function.

(A color version of this figure is available in the online journal.)

Stappers+ 2014

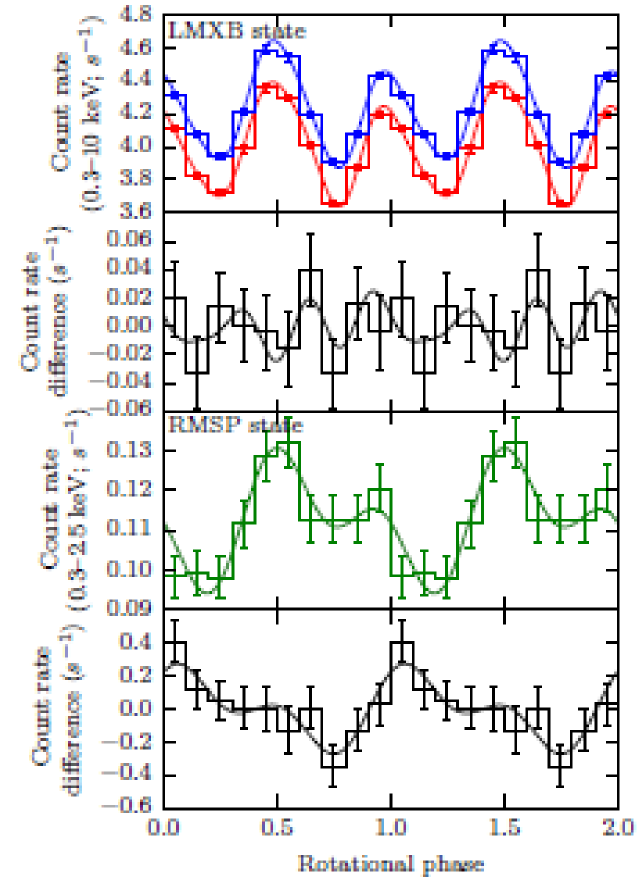


Figure 2. Top panel: the LMXB-state pulse profiles computed from the 2013 November (blue, top) and 2014 June (red,

Archibald+ 2014

XSS J12270-4859 now PSR J1227-4853

Bassa+ 2014

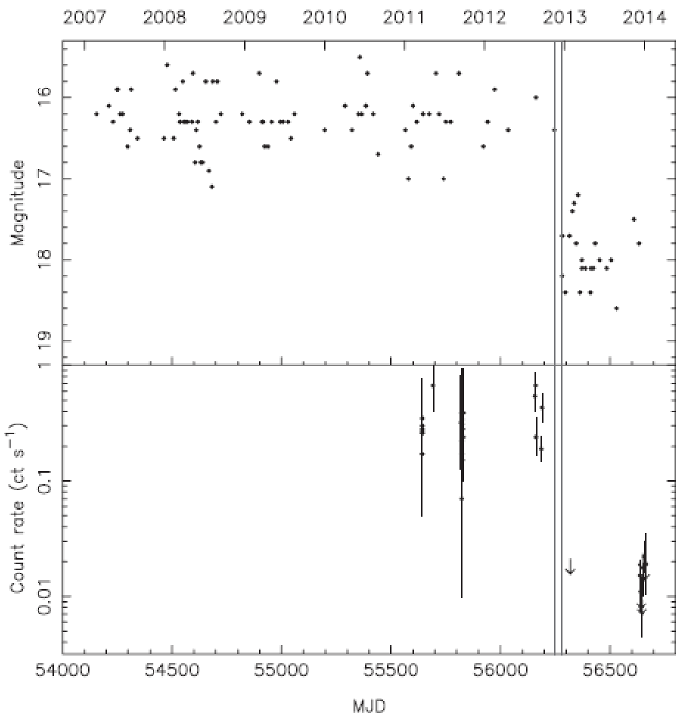
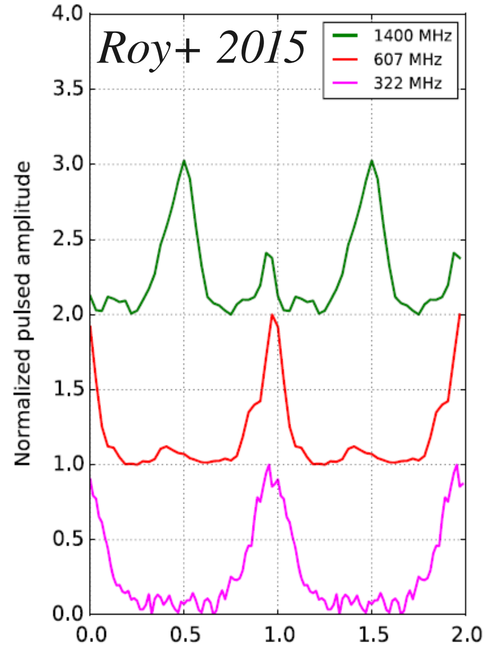
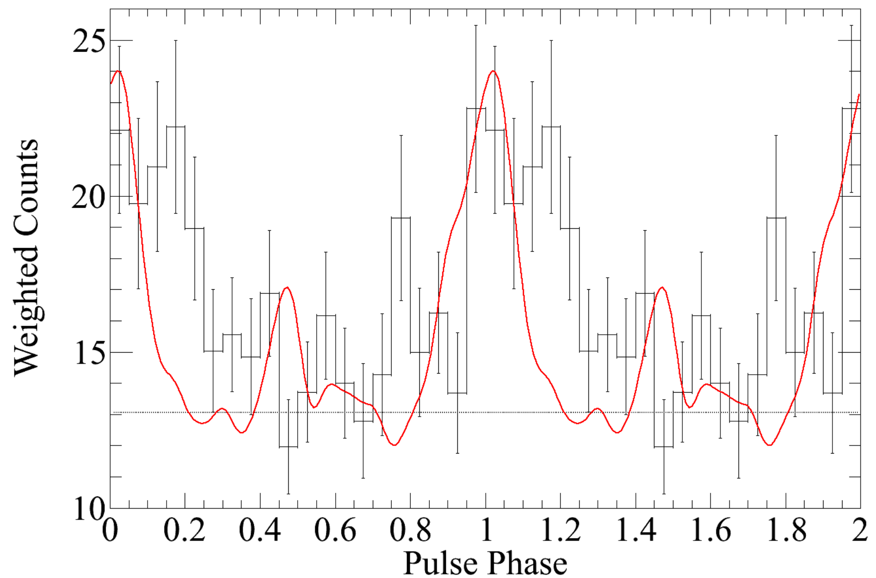


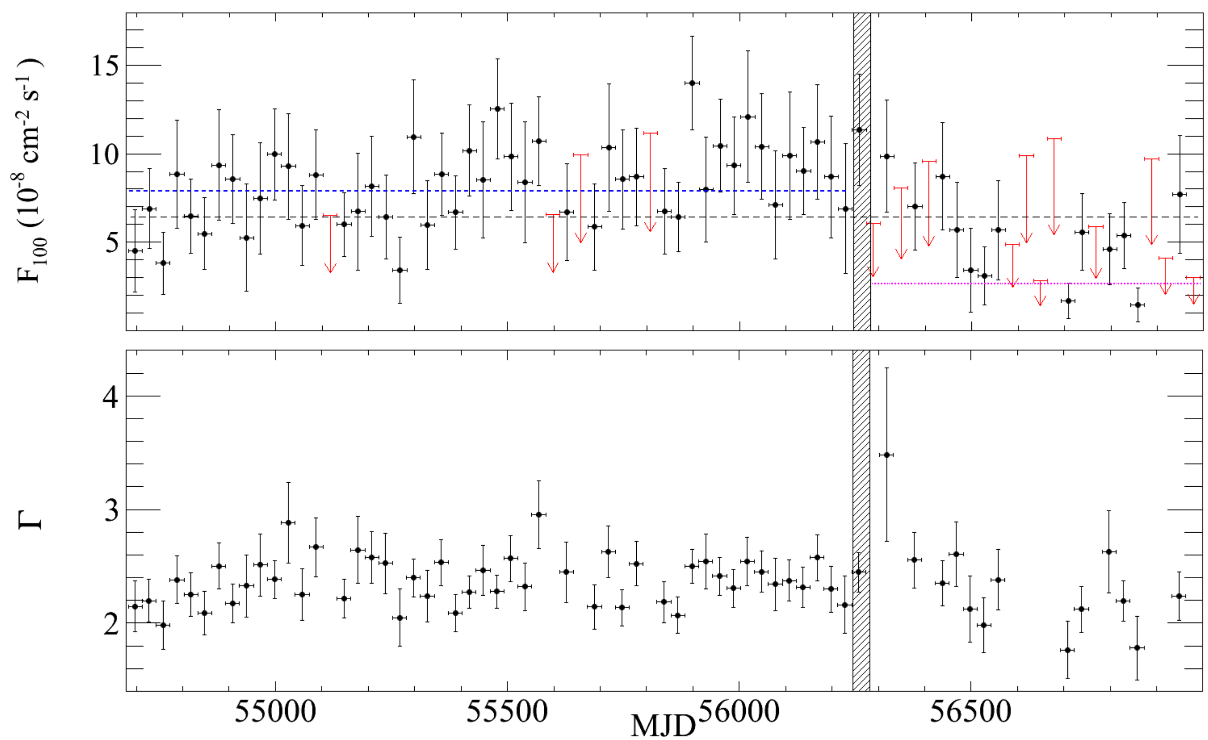
Figure 1. Top panel: the long-term optical light curve of XSS J12270−4859 obtained from the Bronberg and Kleinkaroo Observatories. Unfiltered magnitudes were determined from images obtained with the same telescope and CCD camera combination over the six-year period. The magnitudes were rounded to the nearest 0.1 mag. Typical 1σ magnitude uncertainties were determined from an observation obtained on 2013 February 21, and range from 0.02 mag at 16th magnitude to 0.25 mag at 19th magnitude. A 1.5–2 mag decrease in brightness occurred between 2012 November 14 and December 21. That time period is indicated with the vertical lines. Bottom panel: *Swift*/XRT long-term light curve of XSS J12270−4859 in the 0.3–10 keV energy band. The plot shows an order-of-magnitude decrease in the X-ray count rate that is qualitatively consistent with the decrease in optical brightness. The data prior to 2012 are taken from de Martino et al. (2013a).

Roy+ 2015





Johnson+ 2015



Transitional Pulsars

All three transitional pulsars are RBs

- M28I only one not seen with *Fermi* LAT
- No detectable radio pulsations during accreting phase

X-rays

- At least 10x's brighter during accreting phase
- Sudden dips and flares (on top of orbital modulation)
- Pulsations during high states

Optical

- Brighter (few magnitudes) during accreting phase
- Double humped Hα spectral lines, signature of accretion

γ-rays

- Evidence for spectral curvature, low-levels of flux variability
- No evidence for orbital modulation

Emission Models (I)

Main issue between models – inner disk radius

- Does the accretion disk penetrate the light cylinder?
- Neither predicts orbital modulation, barring eclipse (geometry dependent)
- In both cases, emission is probe of pulsar wind

Takata+ 2014

- Accretion disk outside the light cylinder
  - Rotation-powered pulsar mechanism still on
  - Radio pulsations "smeared out"
- Observed GeV emission is inverse Compton

Papitto+2014

- Disk penetrates light cylinder, mass propelled away by magnetosphere
  - May sometimes accrete, leading to detectable pulsations
- Observed GeV emission is synchrotron-self Compton

Emission Models (II)

Bednarek 2015 (MNRAS Lett. *accepted*, arXiv:1505.01940)

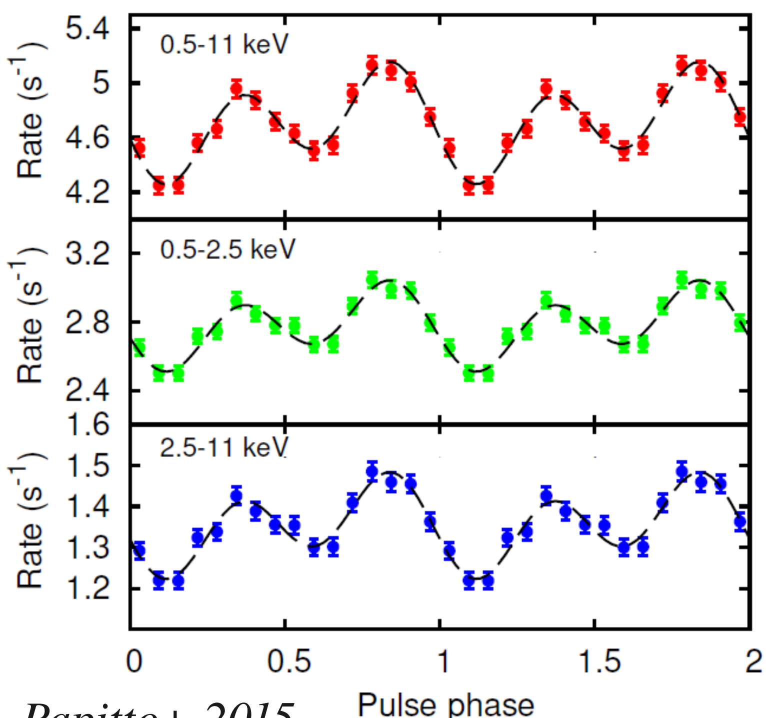
- Accretion disk exists inside the pulsar magnetosphere
  - Able to sometimes reach the surface, X-ray pulsations
  - Transition states initialized by enhanced accretion, roche-lobe overflow
  - Needs close alignment of pulsar spin and magnetic axes
- Rotation-powered pulsar mechanism still active
  - Secondaries from pulsed γ-rays interact with thermal radiation from disk
  - Presupposes slot-gap model, outer gap likely shorted out
    - My be hard to reconcile with presupposed near alignment of axes
  - SED is sum of pulsed emission and IC off of accretion disk

Accretion-Powered Pulsations

Detection of X-ray pulsations during LMXB state

- Most-likely accretion-powered
- Accretion disk penetrates light cylinder (at least sometimes)
    - Rotation-powered pulsar mechanism likely off
- Seems to disfavor model of Takata+ '14

X-ray pulsation from XSS J12270–4859 3



Papitto+ 2015

Figure 2. Background subtracted pulse profile observed during the steady quiescent state of the 2011 *XMM-Newton* observation in the 0.5-11 keV (top panel), 0.5-2.5 keV (middle panel), 2.5-11 keV (bottom panel) energy bands. Two cycles are shown for clarity.

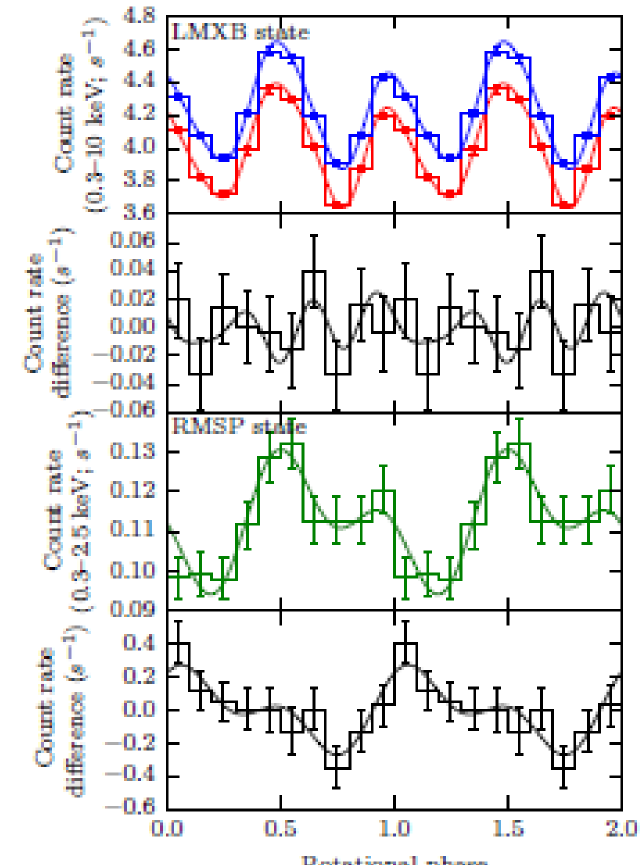


Figure 2. Top panel: the LMXB-state pulse profiles computed from the 2013 November (blue, top) and 2014 June (red,

Archibald+ 2014

Future Prospects

LAT has helped radio astronomers find many new MSPs

- At least 64 new MSPs, most expected to be γ-ray pulsars
- Largely targeting LAT unassociated sources with pulsar-like spectra
- Some good candidates remain unassociated
  - "Radio-quiet"? Obscured?...or RBs in LMXB states?

9 RBs, ~6 years observing, 2 transitions

- Lower limit of 1 transition every 27 years
  - J1023 and J1227 both have 1.6 ms spin period, Porb $<$ 7 hours
  - Assume P $<$ 3 ms and Porb $<$ 7 hours -> 1 transition every 12 years
  - Roughly consistent with observations of J1023

...LAT may observe more transitions

- Monitor known RBs
  - Step in LAT flux, disappearance of pulsations
- Monitor pulsar-like unassociated sources
  - search for orbital periods

Conclusions (I)

Recent advances have revolutionized γ-ray pulsar science

- Largely LAT observations, but also from TeV telescopes
  - From 6 to ~170 pulsars seen to pulse above 100 MeV
  - Emission predominantly outer-magnetospheric
  - MSPs firmly established as a class of γ-ray emitters
    - Singly and in concert from globular clusters

Surprises!

- Pulsations seen at TeV energies
  - Crab, and even Vela above ~40 GeV by HESS
- Pulsar with variable flux
  - "Step" in flux
  - Analogy to radio pulsar mode changes?

Conclusions (II)

Three transitional pulsars have been caught in the act

- All "redbacks", two with correlated γ-ray variability
- Supports MSPs as recycled pulsars
  - What triggers switching? What governs how long it lasts?

GeV emission during the LMXB state

- Few LMXB associations for LAT sources, why these sources
- Probe the pulsar wind

Future transitions

- J1023 had evidence for accretion disk in 2000-2001, transition mid 2013
  - ~Decade timescale
- LAT can monitor known systems & keep an eye out for new ones

Backup Slides

Radio Emission

Pulsar radio emission is:

- coherent, non-thermal (brightness temp >10^{20} K), & often highly polarized
- single-altitude (frequency-dependent)

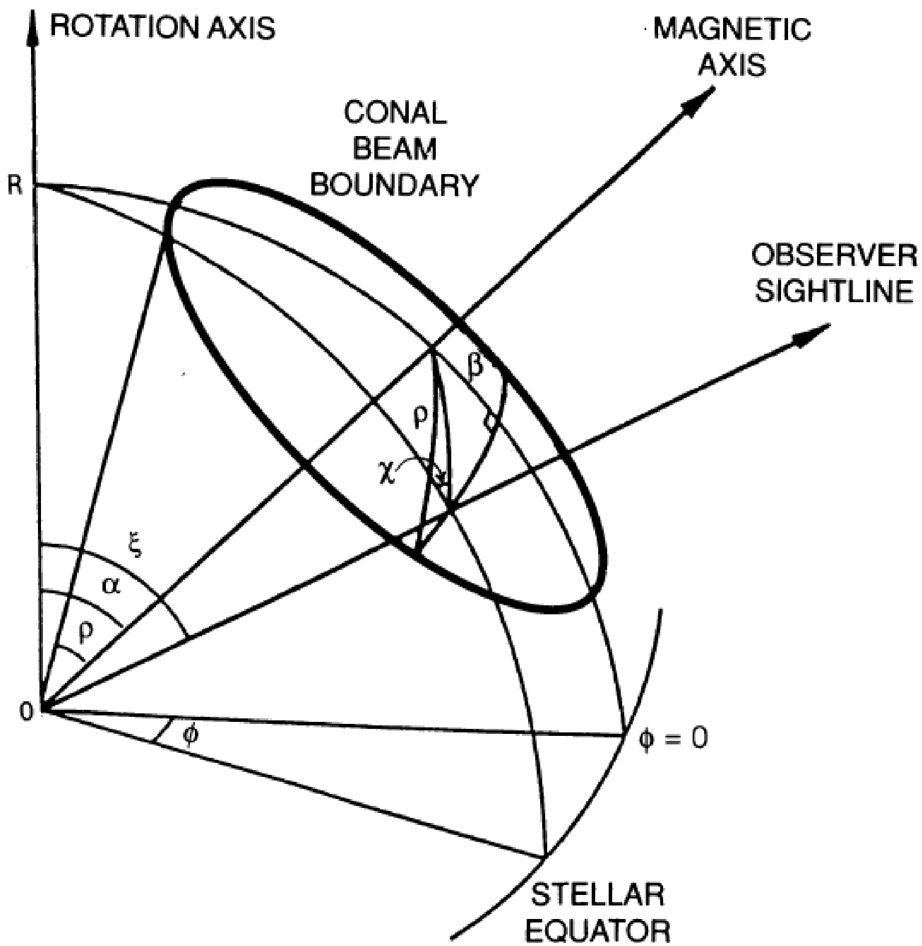
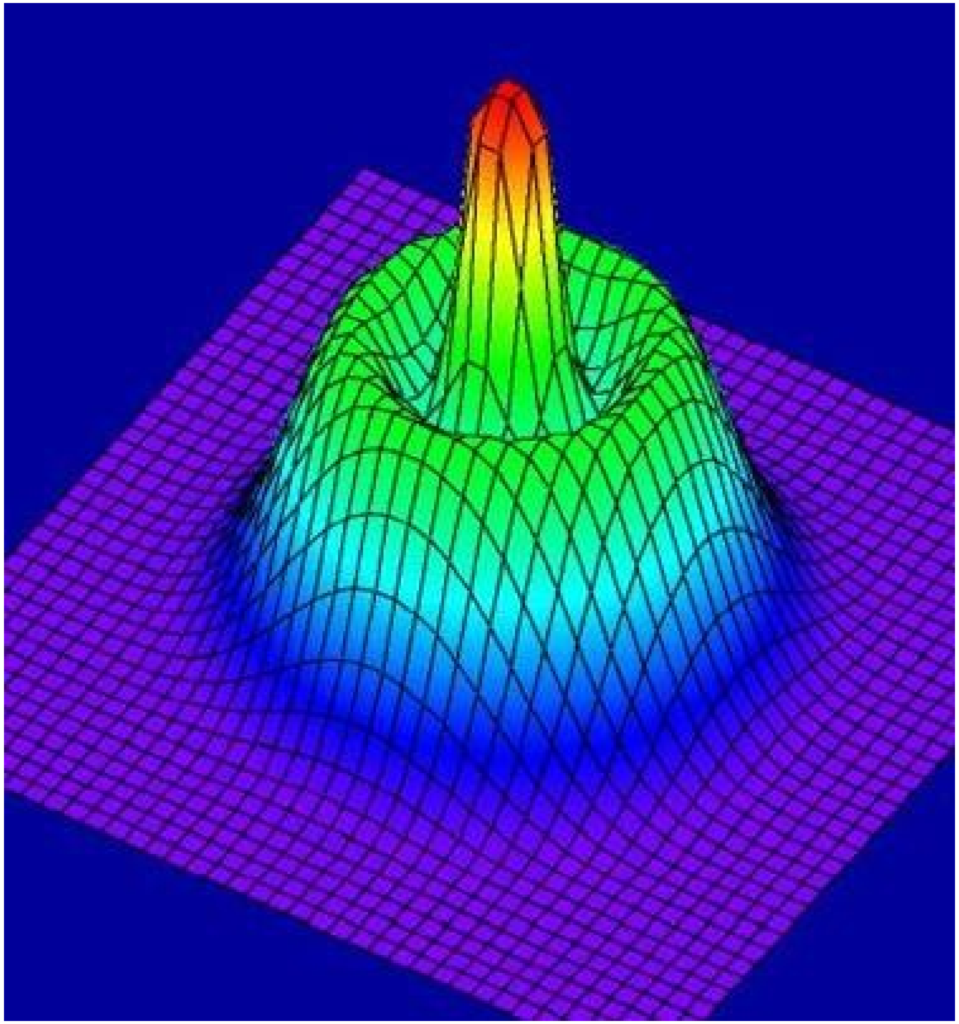


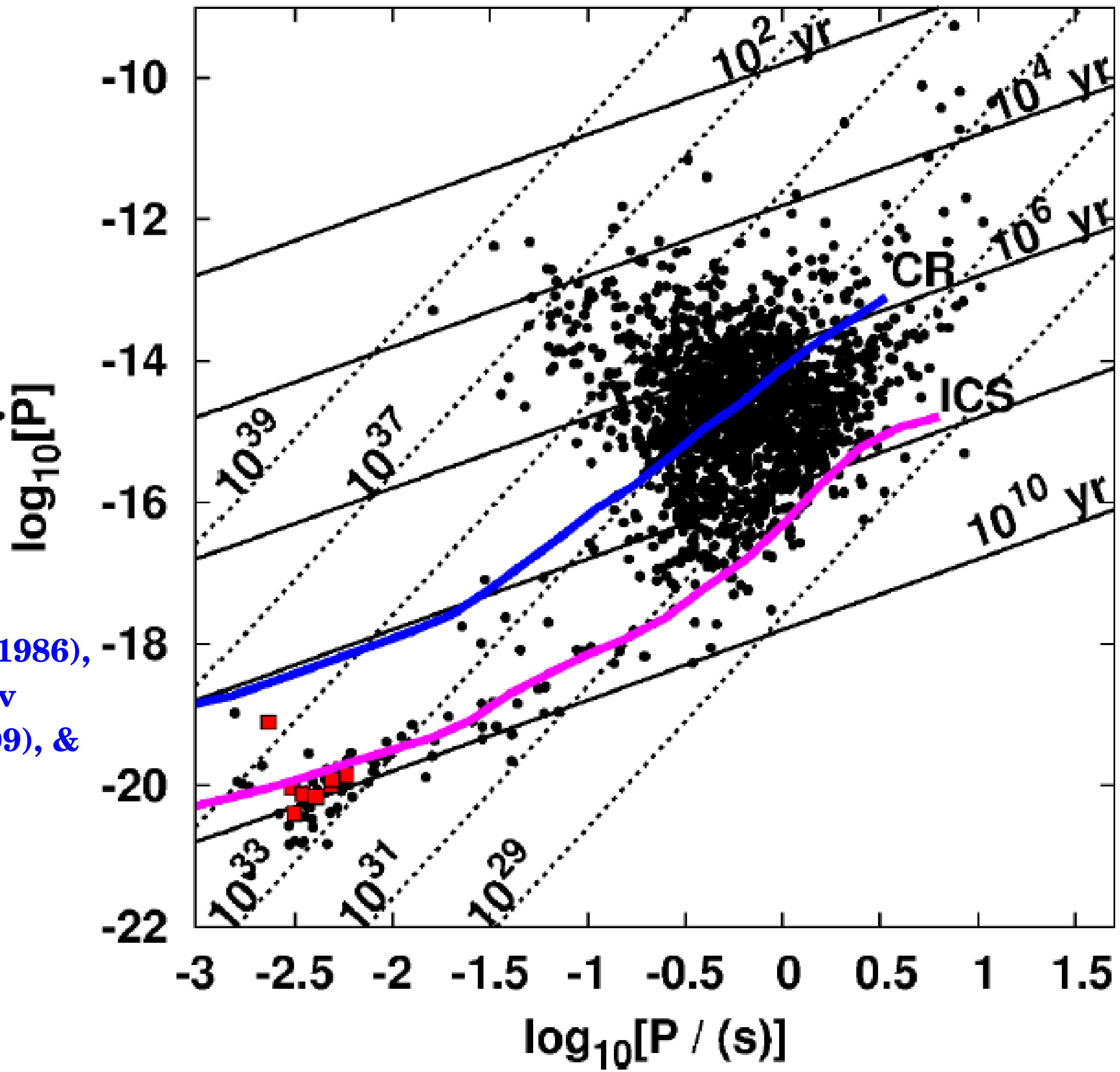
Fig. 2 Rankin (1993)



Screening, not just for the TSA

How do you get vacuum gaps?

Depends on accelerating field strength.

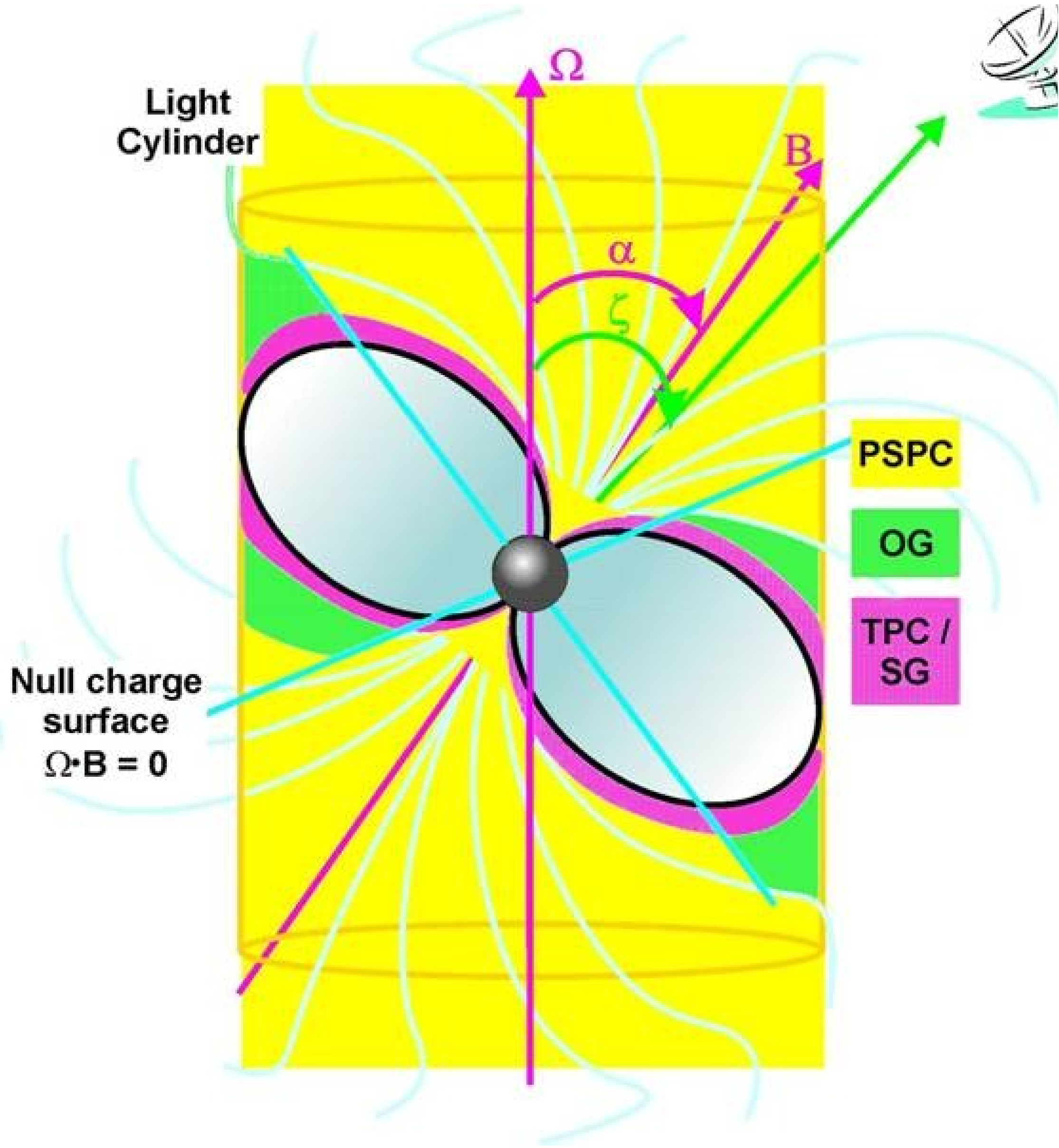


Figs. from Cheng+ (1986), Harding & Muslimov (2003), Harding (2009), & Venter+ (2009)

Emission Without Screening

Pair-starved polar cap – accelerating field unscreened over open volume, particle acceleration and gamma-ray production possible over larger region (e.g., Harding+ 2005)

Suggests broad peaks, slightly leading radio pulse in phase.



New Candidates (I)

The Astrophysical Journal Letters, 788:L27 (5pp), 2014 June 20

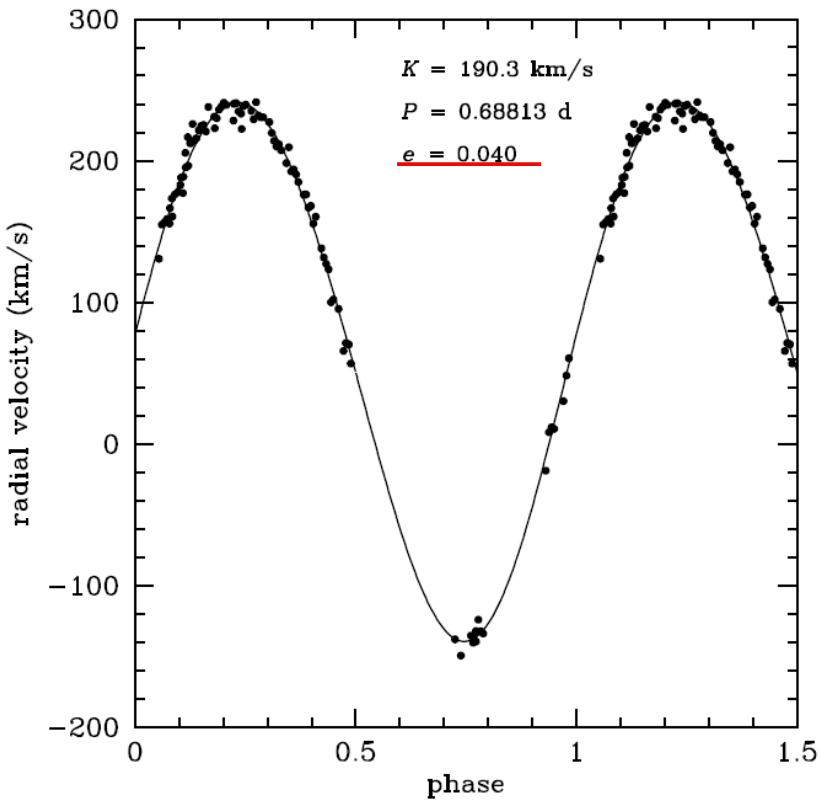


Figure 3. Phased radial velocities for the optical counterpart to 1FGL J0523.5−2529, with the listed Keplerian fit overplotted.

Strader+ 2014

1FGL J0523.5-2529, likely RB

Companion 0.8-0.9 M main sequence star

No evidence for irradiation or accretion disk

Xing+ '14 claim evidence for spectral differences with orbital phase in LAT data

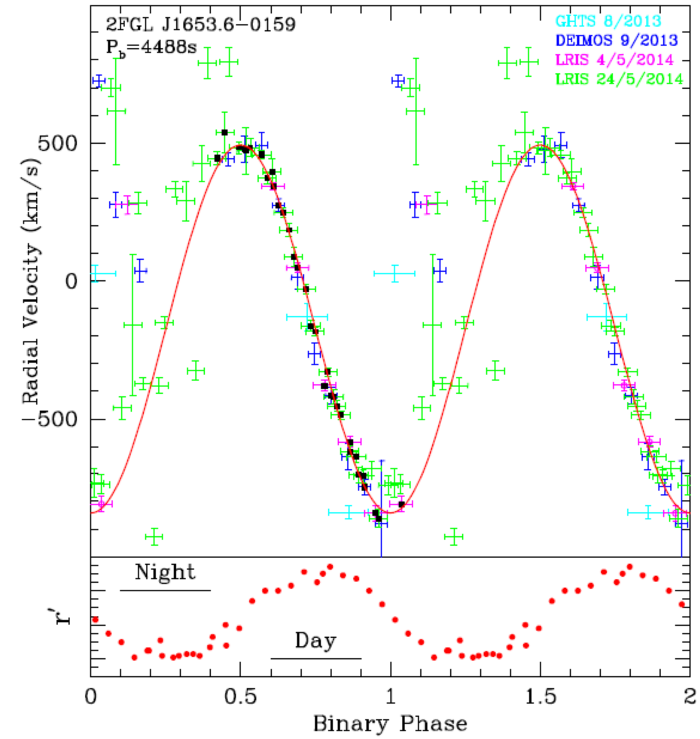


Figure 3. Radial velocities measured by cross-correlation of a K5 V template plotted on the photometric ephemeris of Section 2. The r' light curve is plotted at bottom for reference and two periods are shown. Points with black dots are used to fit K_2 and Γ for the simple sinusoid, shown by the line.

(A color version of this figure is available in the online journal.)

Romani+ 2014

2FGL J1653.6-0159

75 minute orbit, companion irratiated

could be BW or RB

NOTE: At this point, both sources are only positionally associated with the LAT sources

New Candidates (II)

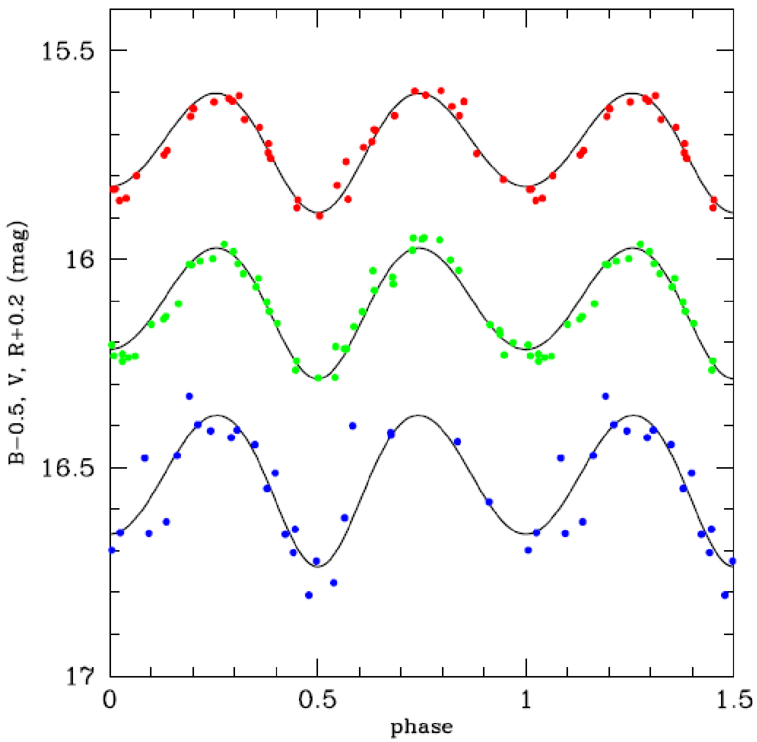


Figure 3. PROMPT photometry in *BVR* (blue, green, and red points) plotted against ellipsoidal models assuming $i = 58^\circ$ and $T_{\rm eff} = 5000$ K. The photometry as plotted is not corrected for foreground reddening.

Strader+ 2015

1FGL J1417.7-4407

Pulsar with giant companion

Not a RB...huntsman?

GeV spectrum not significantly curved

3FGL J1544.6−1125: A Transitional MSP 3

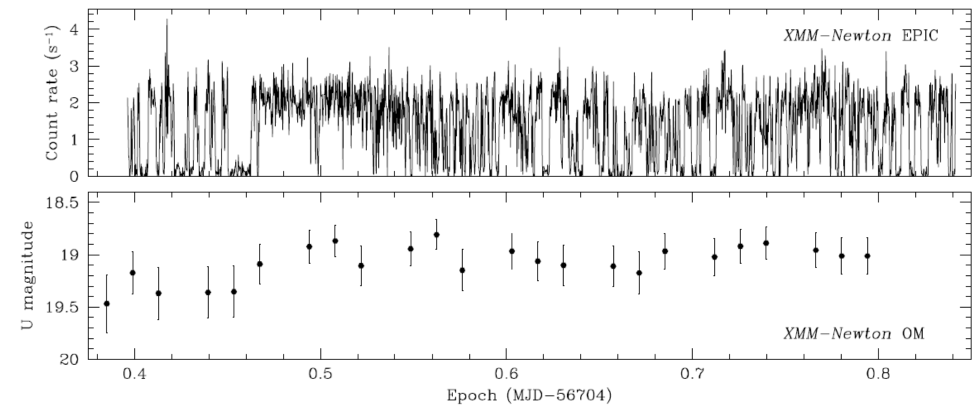


FIG. 2.— Top: Exposure-corrected, background-subtracted 0.3–10 keV X-ray light curve of 1RXS J154439.4−112820 from the *XMM-Newton* EPIC observation obtained by co-adding the MOS1/2 and pn light curves binned at a resolution of 20 seconds. Note the sudden jumps in count rate between ≈0.2 and ≈2 counts s^{-1}. Bottom: *XMM-Newton* OM *U* filter photometric light curve binned at 20 minute resolution.

Bogdanov & Halpern 2015

3FGL J1544.6-1125

GeV spectrum not significantly curved

Optical and X-ray variability similar to J1023 and J1227

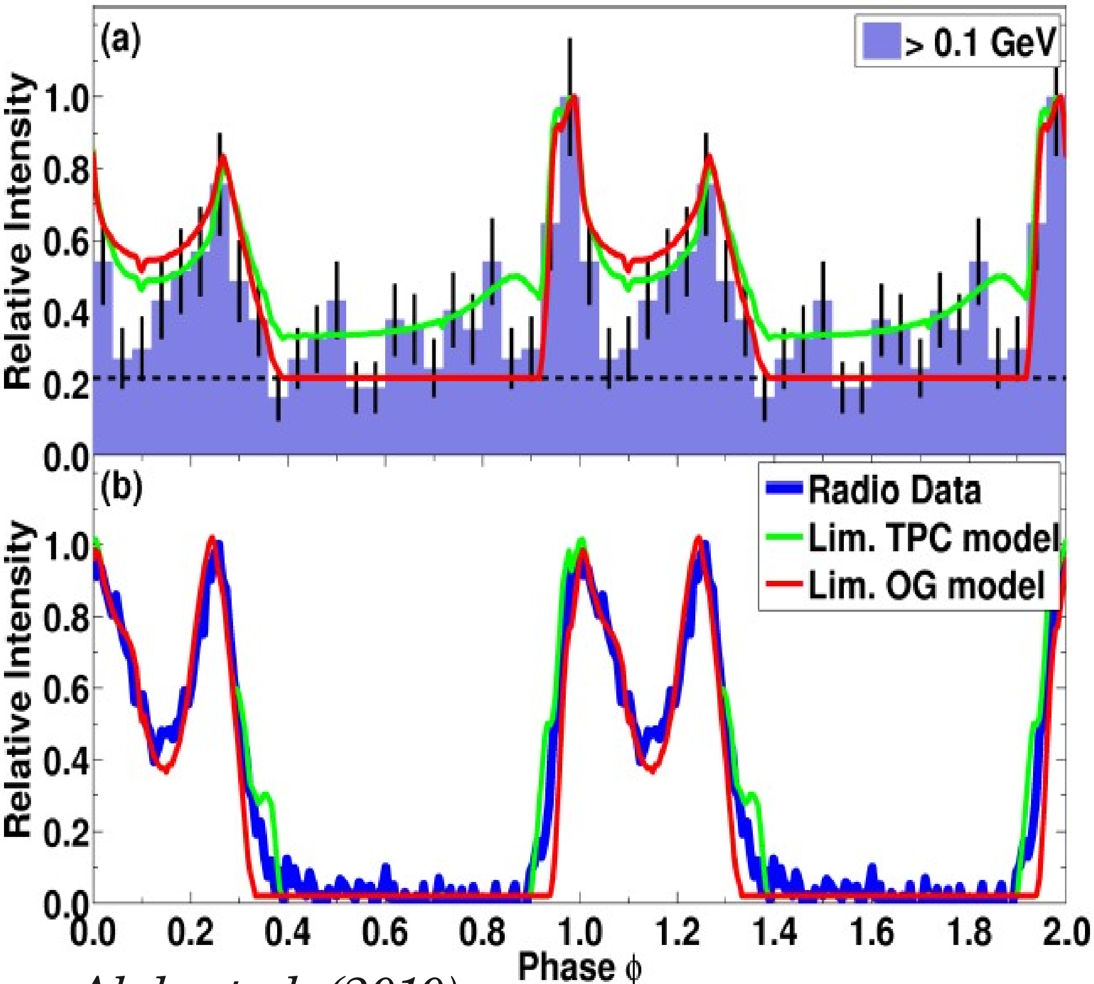
no orbital period detected

optical emission lines suggest presence of accretion disk

NOTE: At this point, both sources are only positionally associated with the LAT sources

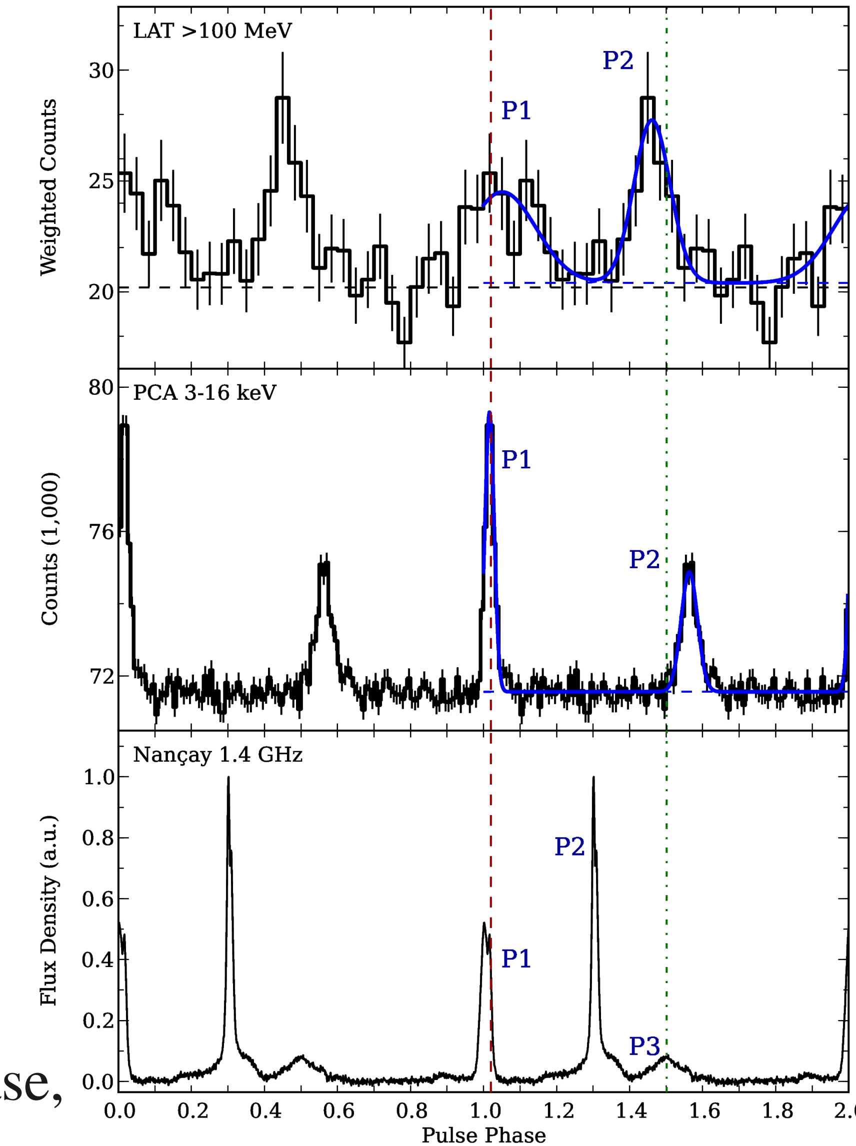
MSPs with aligned peaks

PSR J0034-0534



Abdo et al. (2010)

PSR B1821-24 (in M28)



Johnson et al. (2013)

6 MSPs with radio and g-ray peaks at same phase, 2 with some peaks at same phase, only one non-recycled pulsar (Crab) with aligned peaks