Gamma-ray emission from transitional pulsars

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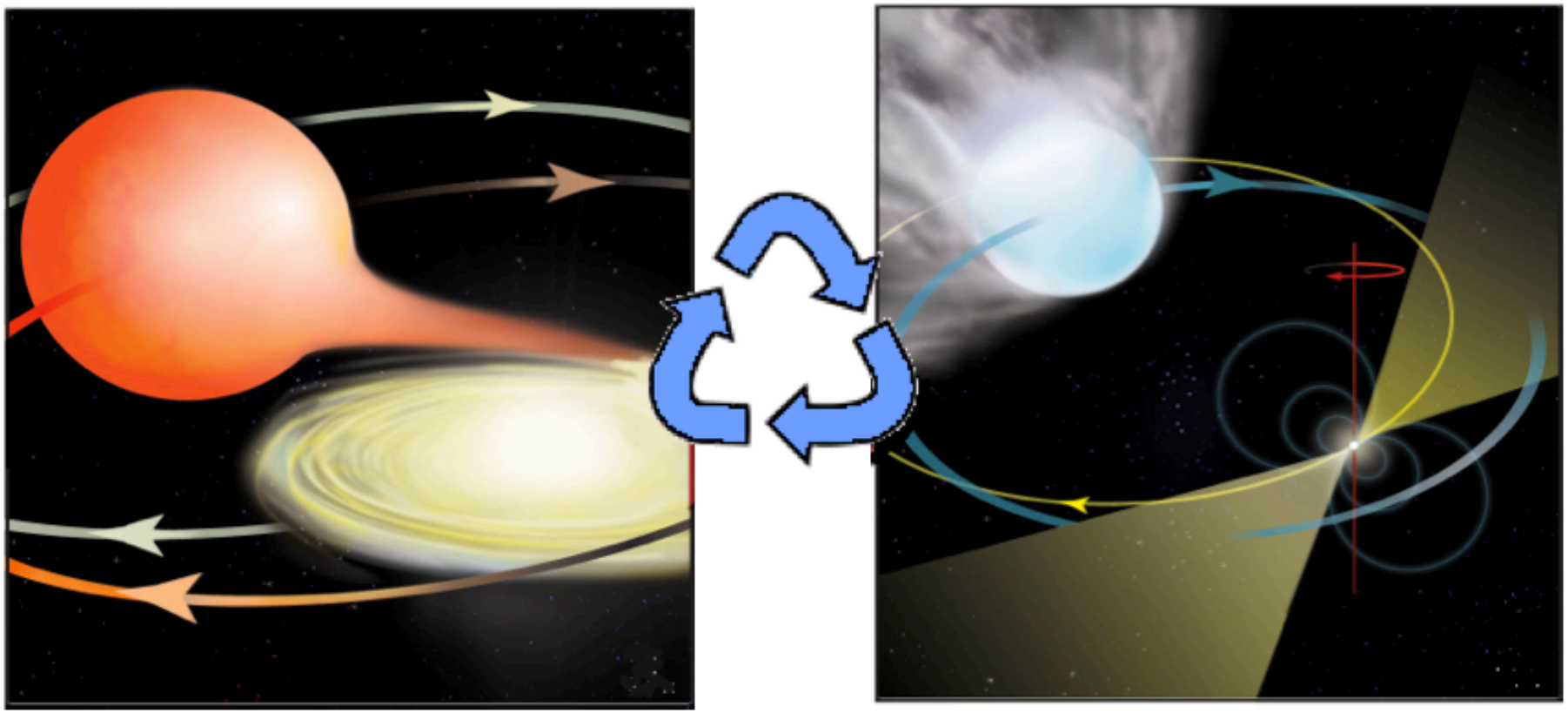
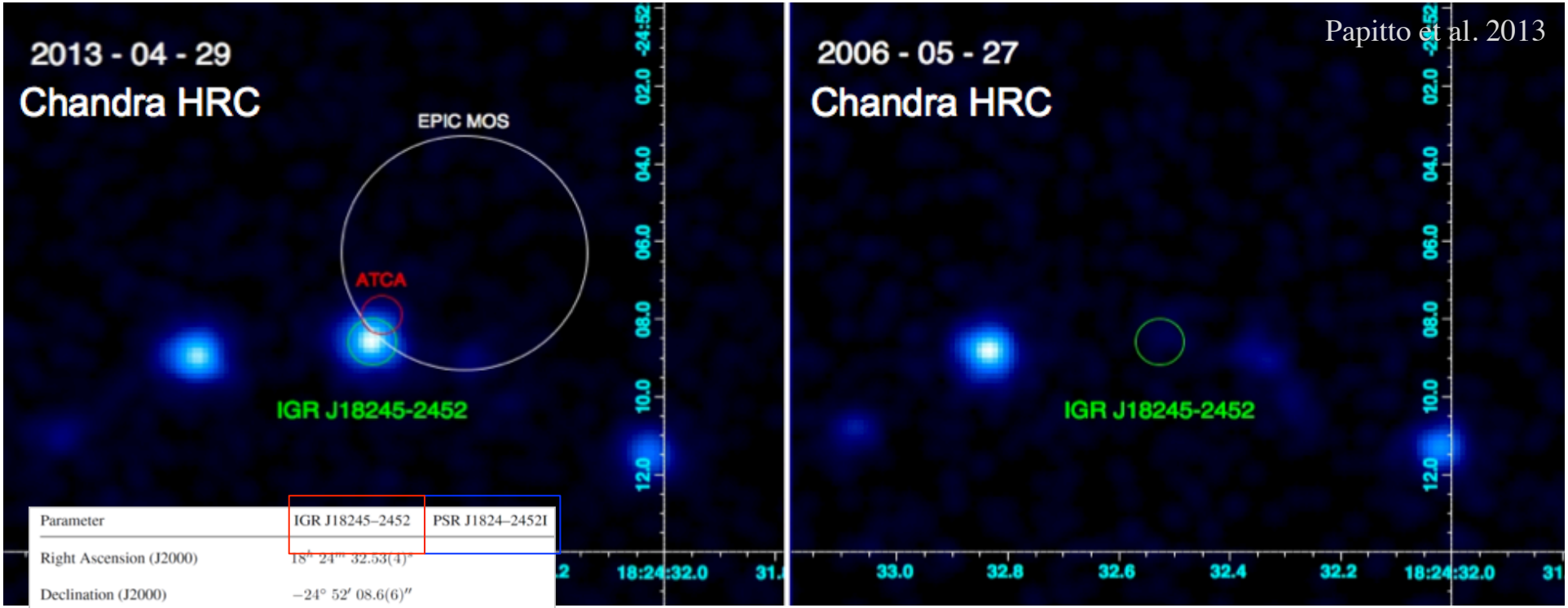
Transitions are central to the recycling scenario for ms pulsars

Balance between gravity and field pressure



IGR J18245-2452 in globular cluster M28: caught in the act



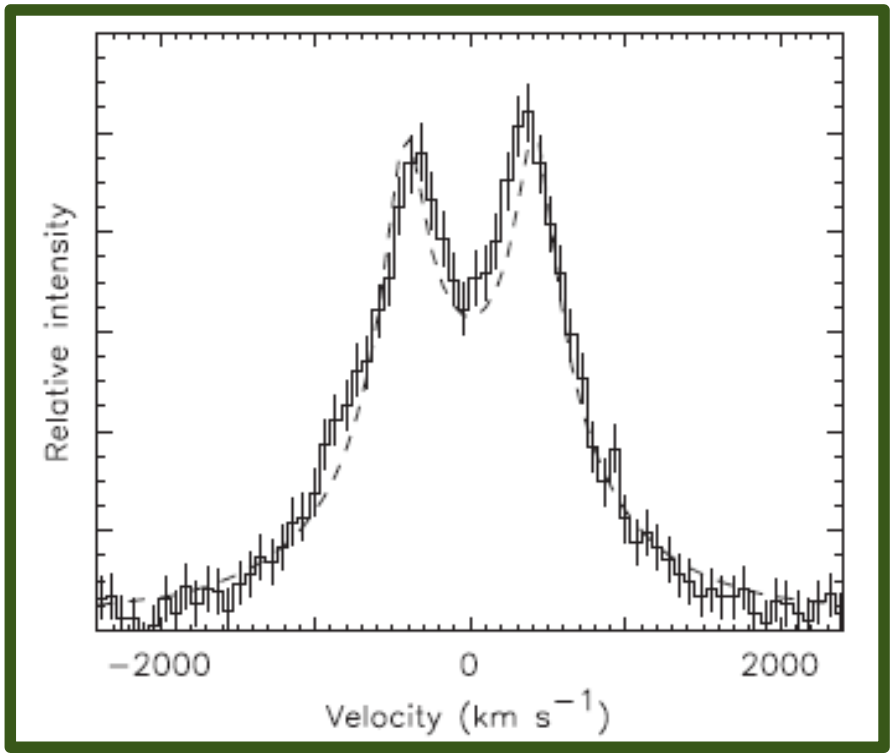
Parameter	IGR J18245–2452	PSR J1824–2452I
Right Ascension (J2000)	$18^h\ 24^m\ 32.53(4)^s$	
Declination (J2000)	$-24°\ 52'\ 08.6(6)''$	
Reference epoch (MJD)	56386.0	
Spin period (ms)	3.931852641(2)	3.93185(1)
Spin period derivative	$< 2 \times 10^{-17}$	
RMS of pulse time delays (ms)	0.1	
Orbital period (hr)	11.025781(2)	11.0258(2)
Projected semi-major axis (lt-s)	0.76591(1)	0.7658(1)
Epoch of zero mean anomaly (MJD)	56395.216889(5)	

+

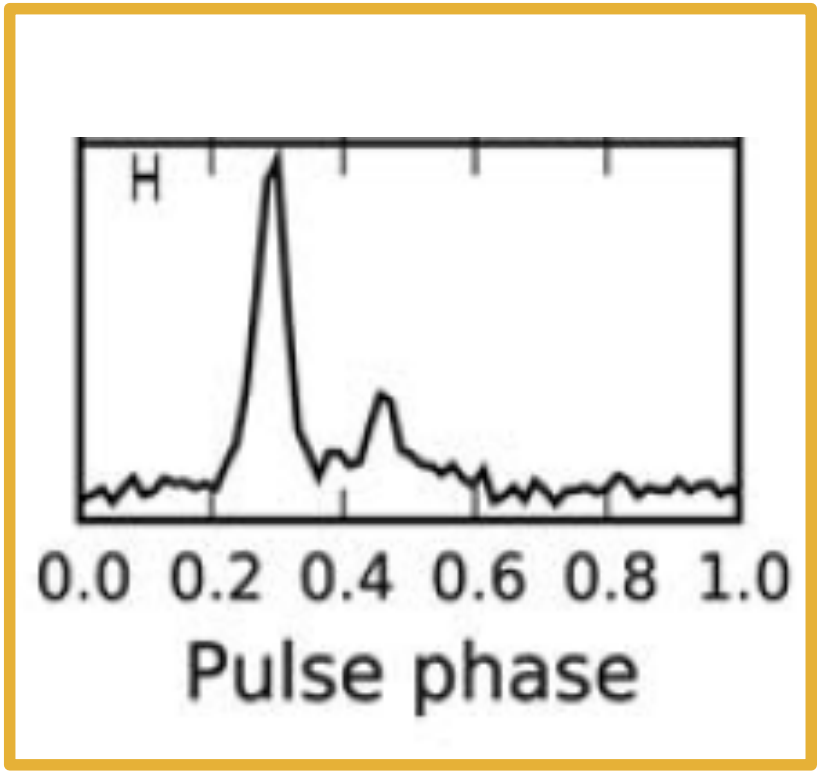
Weak radio signal (~10-50 microJy) detected less than two weeks after the end of the X-ray outburst (GBT, PKS, WSRT).
Papitto et al. 2013, Nature

→ X-ray timing properties found during outburst the same as those catalogued in radio a few years earlier

PSR J1023+0038: indirect evidence of transitions



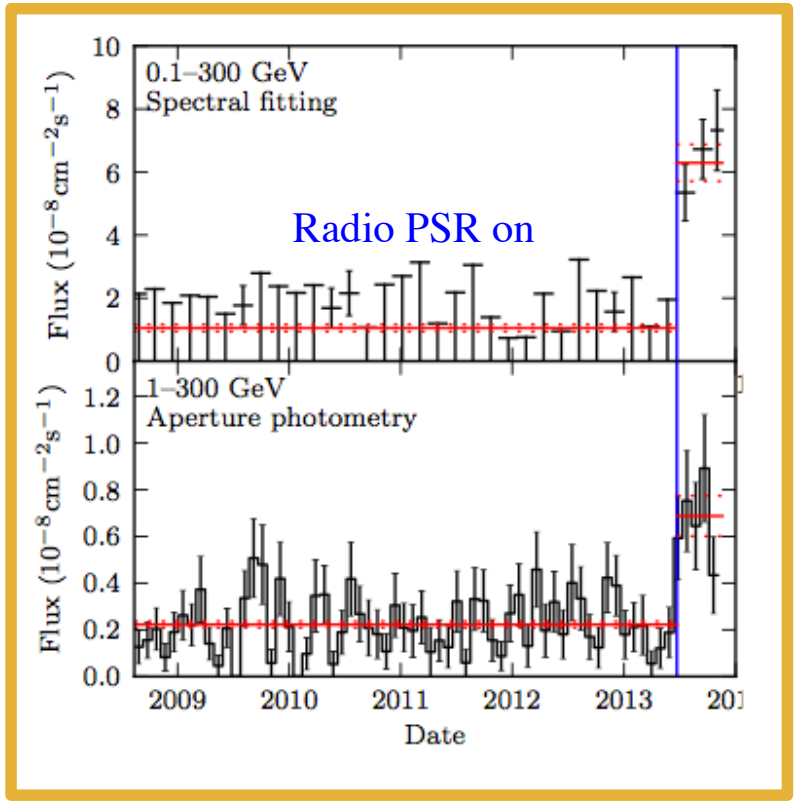
Accretion disk in 2000-2001
(but faint in X-rays, no pulses)



A ~1.7 ms **Radio PSR** in 2009

Implying that a state transition must have occurred,
even if unobserved (Archibald et al. 2009)

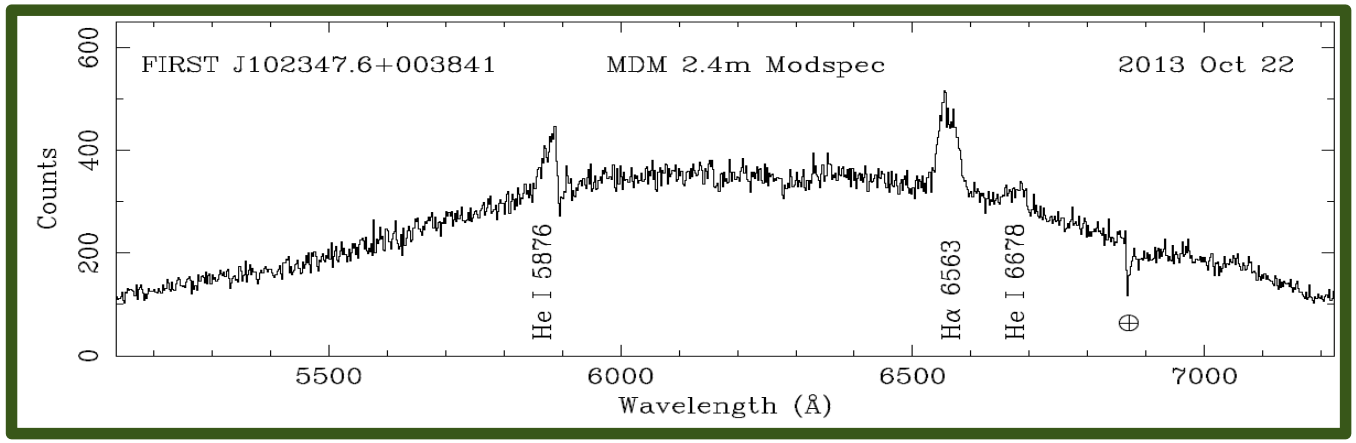
PSR J1023+0038 transitions: gamma-ray emission increase



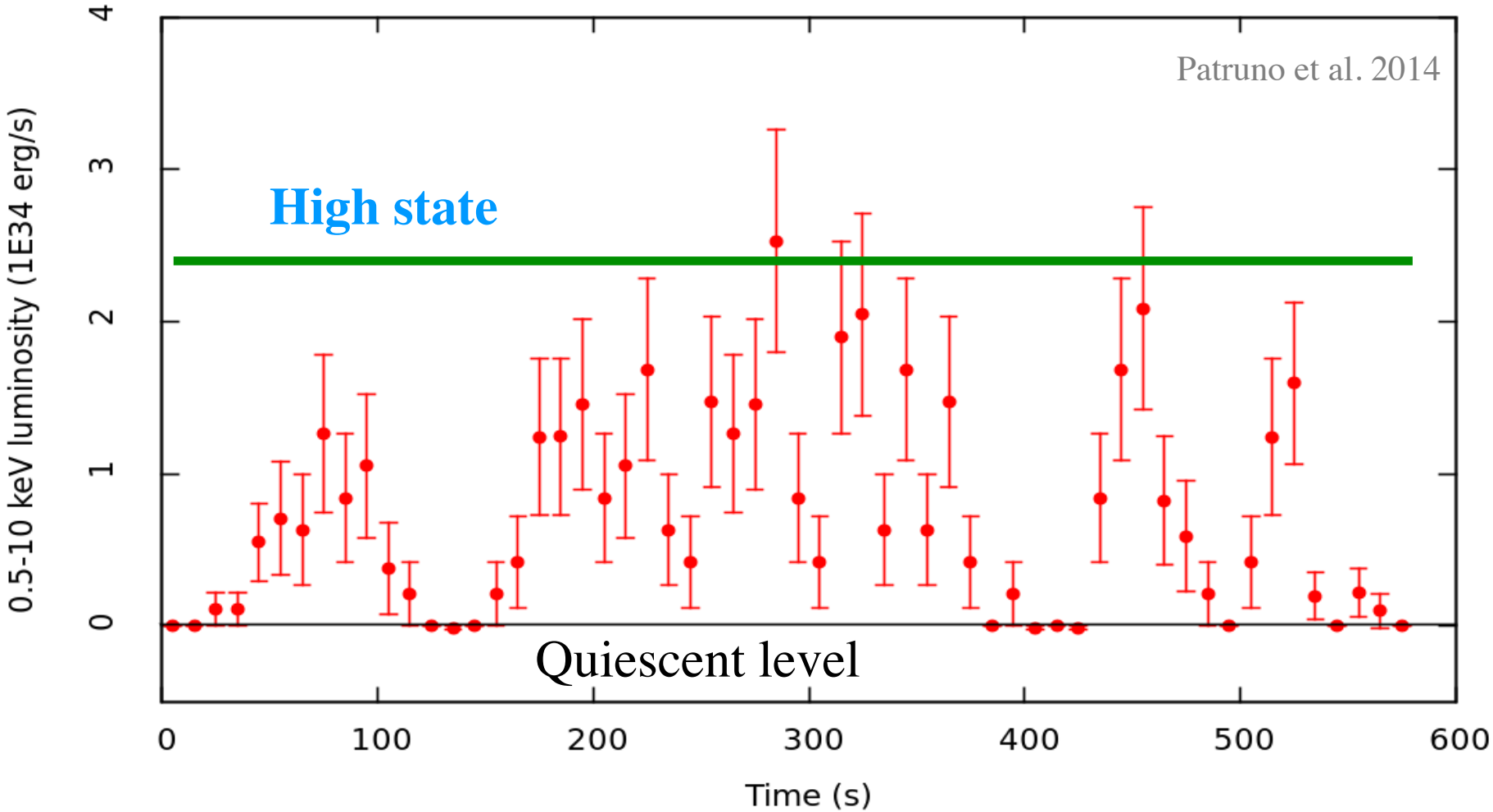
5x increase of gamma-ray flux
(Stappers et al. 2014)

"Whereas until recently the system harbored a bright millisecond radio pulsar, the radio pulsations at frequencies between 300 to 5000 MHz have now become undetectable. Concurrent with this radio disappearance, the γ-ray flux of the system has quintupled."

Broad double-peaked optical emission lines
(Halpern et al. 2013)



PSR J1023+0038 transitions: X-ray variability



At peak → $L_X \sim 10^{34}$ erg/s → Accretion power (compatible with propeller)

At minimum → $L_X \lesssim 3\text{x}10^{32}$ erg/s (compatible with rotation-power)

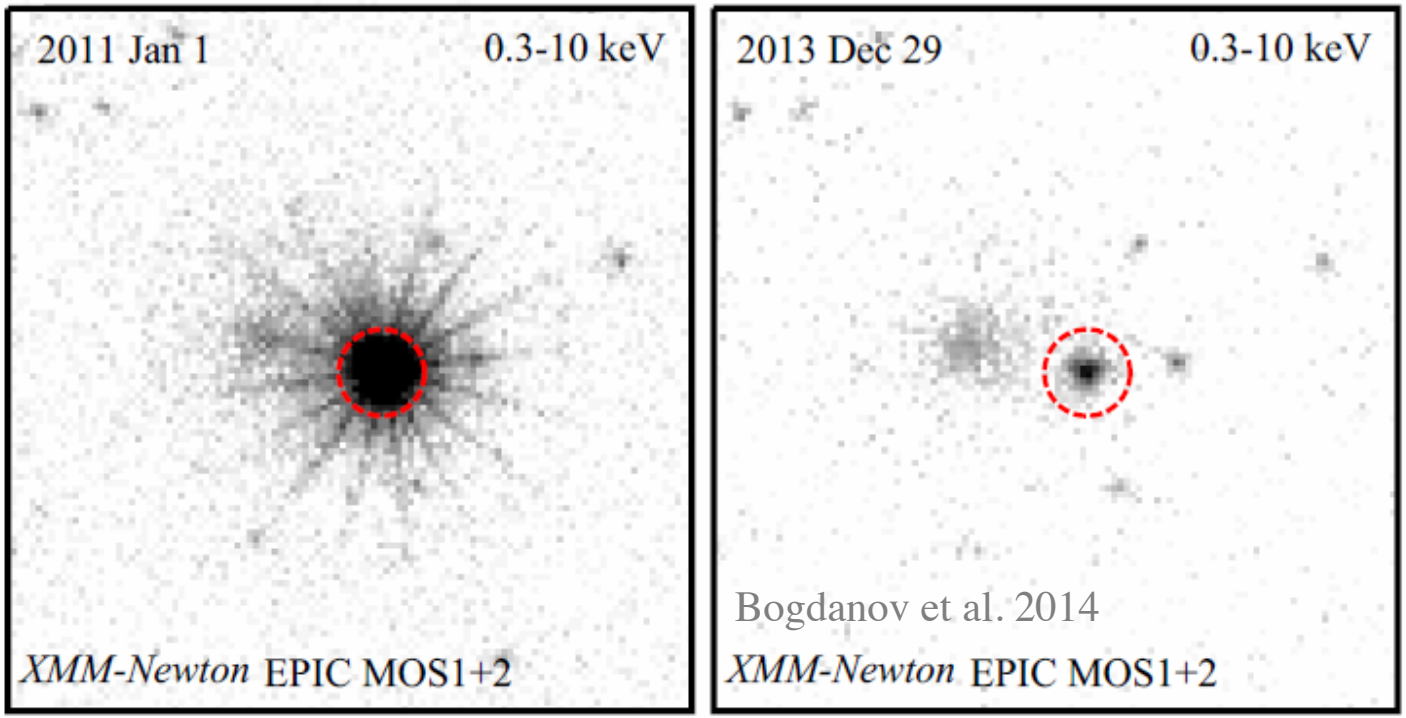
A third transitional pulsar: XSS J12270-4859 (twin of J1023)

Sub-luminous (~10^{34} erg/s) in X-rays
- X-ray variability
- Low mass companion and disk
- Gamma-ray bright

[De Martino+2010,2013; Saitou+2010; Hill+2011]

Detected as a **Radio PSR**
faint in X-rays (~10^{32} erg/s)
No disk

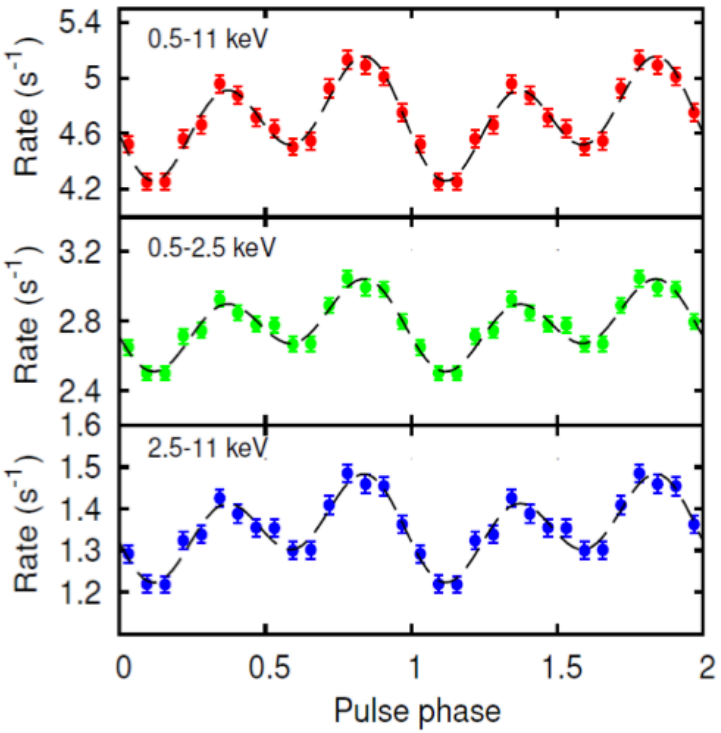
[Bassa+2014, Bogdanov+2014, Roy+ 2014]



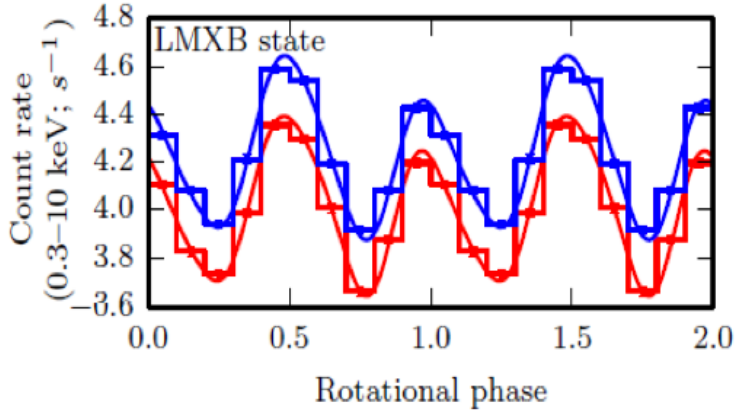
Bogdanov et al. 2014

Detection of X-ray pulsations during sub-luminous state

XSS J12270-4859
Papitto et al. 2015



PSR B1023+0038
Archibald et al. 2015



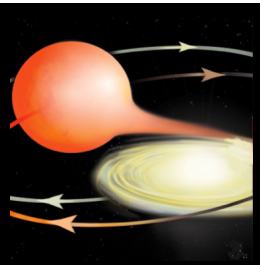
Coherent pulsations with rms amplitude ~10%

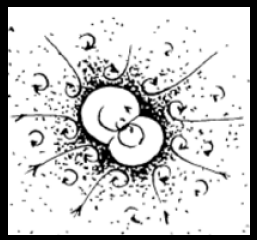
The three stages of transitional pulsars

Accretion powered state

Bright X-ray outburst (~10^{36} erg/s)

X-ray pulsations





An intermediate (propeller?) state

Sub-luminous accretion (~10^{34} erg/s)

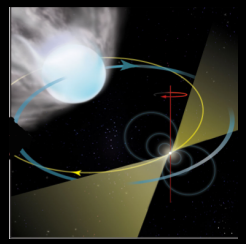
Brighter gamma-ray emission

X-ray pulsations (10% level)

Rotation powered state

Faint in X-rays (~10^{32} erg/s)

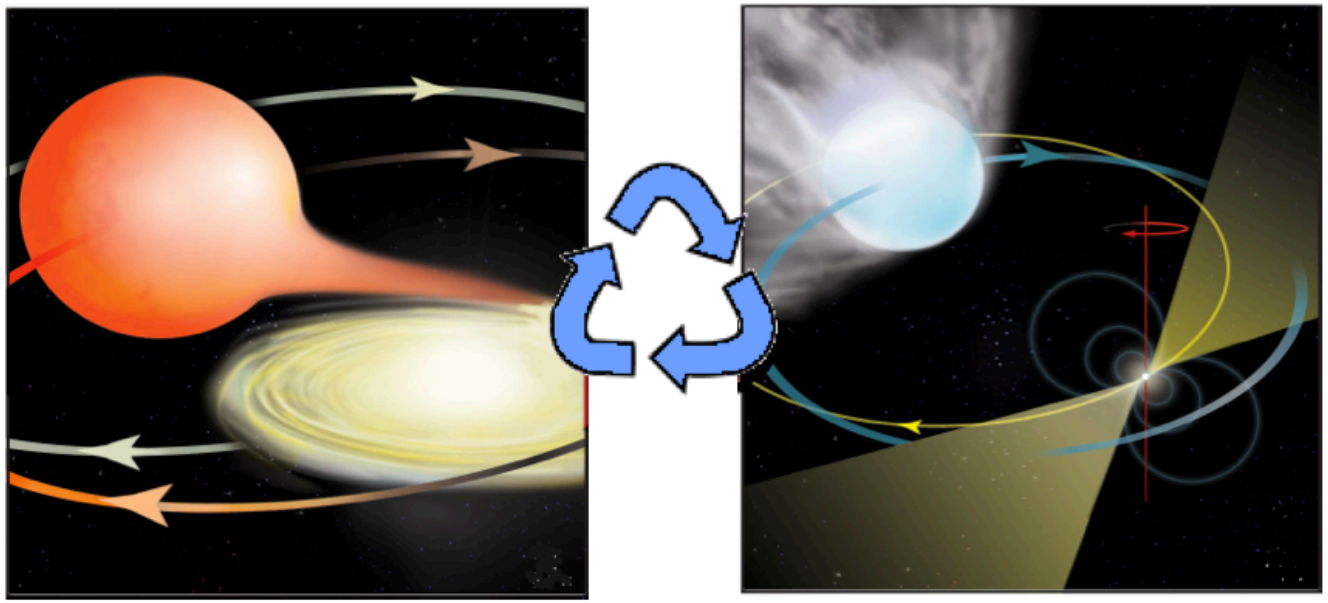
Radio/gamma-ray pulsations



Leading questions

- What powers the emission of the Transitional PSRs?
- How, where, and when are particles accelerated?
- What process(es) yield the highest energy photons?

Balance between gravity and field pressure



Accretion and rotation power alternate over timescales as short as few weeks

The sub-luminous disk state showed by the transitional PSRs

• **Presence of an accretion disk**: Hα broad, sometimes double peaked emission lines observed in the optical spectrum (Wang et al. 2009; Pallanca et al. 2013; Halpern et al. 2013; De Martino et al. 2014)

• **Average X-ray luminosity 10^{33} to 10^{34} erg s^{-1}**, intermediate between the peak of X-ray outbursts (10^{36} erg s^{-1}) and the rotation powered emission (<10^{32} erg s^{-1});

the X-ray emission is variable on timescales of few tens of seconds and has a spectrum described by a power-law with index $\Gamma \simeq 1.5$ and no cut-off below 100keV (Saitou et al. 2009; De Martino et al. 2010, 2013; Papitto et al. 2013; Linares et al. 2014; Patruno et al. 2014; Tendulkar et al. 2014)

• **Presence of accretion-driven X-ray coherent pulsations** at an rms amplitude btw 5 and 10 per cent, detected from the two sources that were observed at a high-enough temporal resolution, PSR J1023+0038 and XSS J12270-4859 (Archibald et al. 2014, Papitto et al. 2015)

• **0.1-10 GeV luminosity of ≈ 10^{34} erg s^{-1}**, ten times brighter with respect to the level observed during the rotation powered state (De Martino et al. 2010; Hill et al. 2011, Papitto, DFT & Li 2014, Stappers et al. 2014; Takata et al. 2014). Transitional pulsars are the only low-mass X-ray binaries from which a gamma-ray emission has been detected so far by Fermi/LAT.

• **a bright, flat-spectrum radio emission indicative of partially absorbed synchrotron emission**; transitional ms pulsars in this state are 1-2 orders of magnitude brighter at radio frequencies with respect to the extrapolation of the radio/X-ray correlation observed from X-ray brighter NS (Deller et al. 2014).

Limits to accreted matter flow from the detection of pulses

Assuming that the coherent X-ray pulsations observed from PSR J1023+0038 in the disk state were due to accretion of matter onto a fraction of the NS surface

We can compute a lower (upper) limit to the mass accretion rate onto the NS: $\dot{M}_{NS}$

- Lower limit: only pulsed luminosity (~6% of L_x) represents the NS accretion rate
- Upper limit: the total X-ray luminosity L_x represents the NS accretion rate

$$L_X(0.3-79\ \mathrm{keV})=7.3\times10^{33}\ \mathrm{erg\ s^{-1}}$$

$$5\times10^{-14}\mathrm{M_\odot\ yr^{-1}} \simeq (\sqrt{2}A_{rms})\frac{L_X R_{NS}}{GM_{NS}} < \dot{M}_{NS} < \frac{L_X R_{NS}}{GM_{NS}} \simeq 6\times10^{-13}\mathrm{M_\odot\ yr^{-1}}$$

So that R_{in} is within a factor of a few equal to co-rotation radius, the disk mass accretion should

$$R_{in}=k_m R_A = k_m\left[\frac{\mu^4}{2GM_*\dot{M}_d^2}\right]^{1/7} < R_c=(GMP^2/4\pi^2)^{1/3}$$

$$\dot{M}_d \simeq 7\times10^{-11}\ \mathrm{M_\odot\ yr^{-1}} > 100\times\dot{M}_{NS}$$

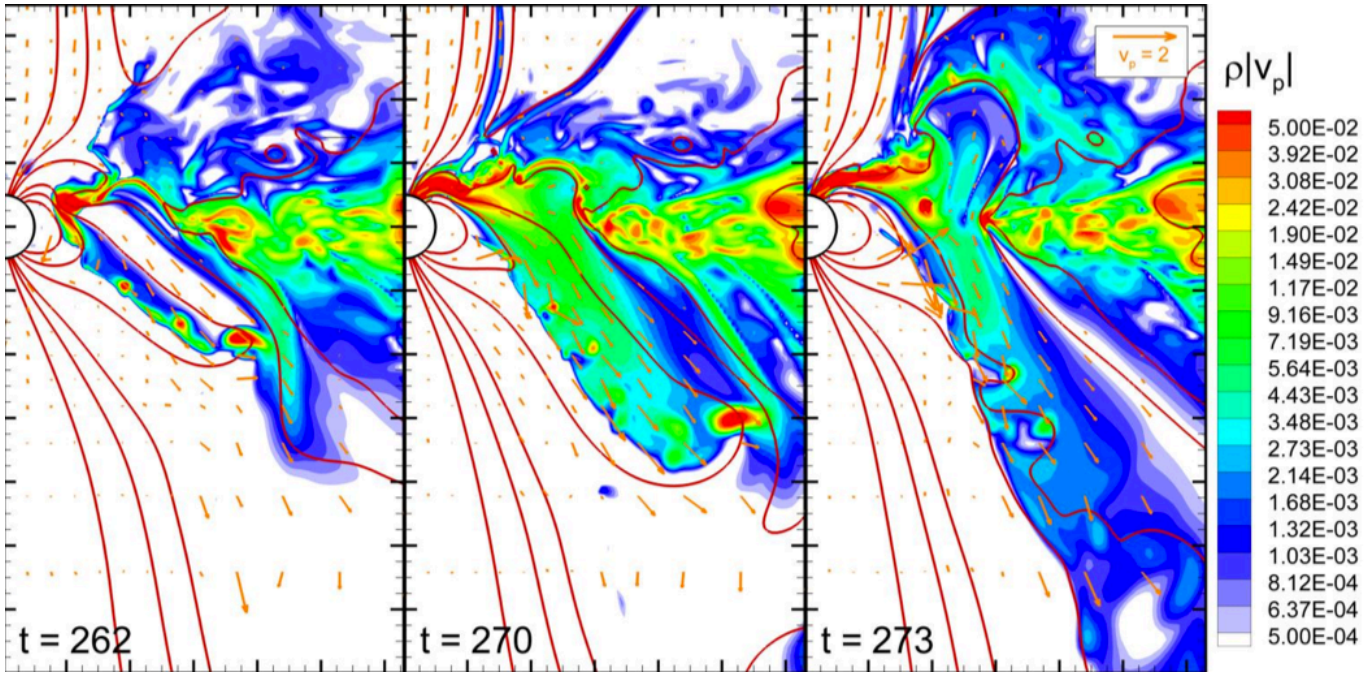
$\gtrsim$ 99 % of the matter in-flowing in the disk must be ejected

Propeller outflows can co-exist with partly accreted matter

Lii, Romanova+ 2014 showed in MHD simulations that when the centrifugal barrier is overcame, matter enters into the magnetosphere. Part is accreted, part is launched in an outflow.

Accretion and outflows can coexist

The larger the fastness, the larger is the fraction of the mass that is ejected



Model build up: energy and mass conservation

1 $$L_{prop} + L_d + \dot{E}_{adv} + L_{NS} + \frac{1}{2}\dot{M}_{ej}v_{out}^2 = \dot{E}_g + N\Omega_*$$

Energy conservation

The energy to power the radiative emission from the disk (L_d), the inner disk boundary (L_{prop}), the NS surface (L_{NS}), the kinetic energy of the outflow (M_{ej} v^2 /2), and that converted into internal energy of the flow and advected (E_{adv})

=

Gravitational energy liberated by in-fall of matter, plus the energy release by the magnetosphere through the torque N

$$\dot{M}_d = \dot{M}_{NS} + \dot{M}_{ej}$$

Mass conservation

the fraction of mass ejected as

$$k_{ej} = \frac{\dot{M}_{ej}}{\dot{M}_d} = 1 - \frac{\dot{M}_{NS}}{\dot{M}_d}$$

$k_{ej} > 0.95$ for PSR J1023+0038

the gravitational energy liberated by the mass in-fall

$$\dot{E}_g = \frac{GM\dot{M}_d}{R_{in}} + GM\dot{M}_{NS}\left(\frac{1}{R_{NS}} - \frac{1}{R_{in}}\right)$$

the NS luminosity is given by efficient conversion of the in-falling grav. energy

$$L_{NS} = GM\dot{M}_{NS}\left(\frac{1}{R_{NS}} - \frac{1}{R_{in}}\right)$$

Model build up: disk & propeller luminosities

express the disk lum. as a fraction η of the energy radiated by an optically thick, geometrically thin disk

$$L_d = \eta \frac{GM\dot{M}_d}{2R_{in}}$$

The case of a radiatively efficient disk is realized for η = 1.

For values of η lower than unity, the energy that is not radiated by the disk is partly advected, and partly made available to power the propeller emission.

$$\dot{E}_{adv} = (1 - \eta - \xi)\frac{GM\dot{M}_d}{2R_{in}}.$$

$$L_{prop} + L_d + \dot{E}_{adv} + L_{NS} + \frac{1}{2}\dot{M}_{ej}v_{out}^2 = \dot{E}_g + N\Omega_*$$

$$L_{prop} = \left(\frac{1+\xi}{2}\right)\frac{GM\dot{M}_d}{R_{in}} + N\Omega_* - \frac{1}{2}k_{ej}\dot{M}_d v_{out}^2$$

Energy conservation

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$$L_{prop} = \left(\frac{1+\xi}{2}\right)\frac{GM\dot{M}_d}{R_{in}} + N\Omega_* - \frac{1}{2}k_{ej}\dot{M}_d v_{out}^2$$

? ?

Energy conservation

Model build up: momentum conservation

2 $$\dot{M}_{ej} R_{in} v_{out} = N + \dot{M}_d \Omega_K R_{in}^2$$

Angular momentum conservation at the inner disk boundary

$\Omega_K = \sqrt{GM/R_{in}^3}$

Rate of angular momentum in the outflow = Torque applied by the magnetic field plus angular momentum carried by disk matter

- Eksi et al. (2005) treated the interaction at the inner disk boundary as a collision of particles, and expressed the outflow velocity as:

$$v_{out} = \Omega_K(R_{in}) R_{in} [1 + (1+\beta)(\omega_* - 1)]$$

$$\omega_* = \frac{\Omega_*}{\Omega_K(R_{in})} = \left(\frac{R_{in}}{R_{co}}\right)^{3/2}$$

Fastness

$R_c = (GM_*/\Omega_*^2)^{1/3}$

- β is the elasticity parameter. Anelastic collision is given by β = 0. Elastic case is described by β = 1.

Model build up: momentum conservation

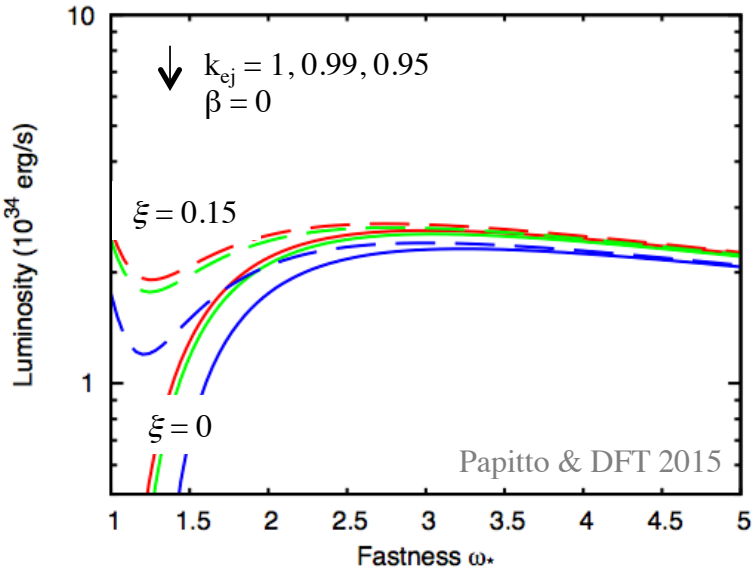
Using the former expressions into the conservation relations

1 2 $\longrightarrow$ $$L_{prop} = \frac{GM\dot{M}_d}{R_{\rm in}} \left\{ \frac{1+\xi}{2} - \omega_* + k_{ej} \left[\omega_*[\omega_*(1+\beta) - \beta] - \frac{1}{2}[\omega_*(1+\beta) - \beta]^2 \right] \right\}$$

$$N = \dot{M}_d \sqrt{GMR_{in}} \{ k_{ej}[\omega_*(1+\beta) - \beta] - 1 \}$$

Using $k_{ej} \rightarrow 1$

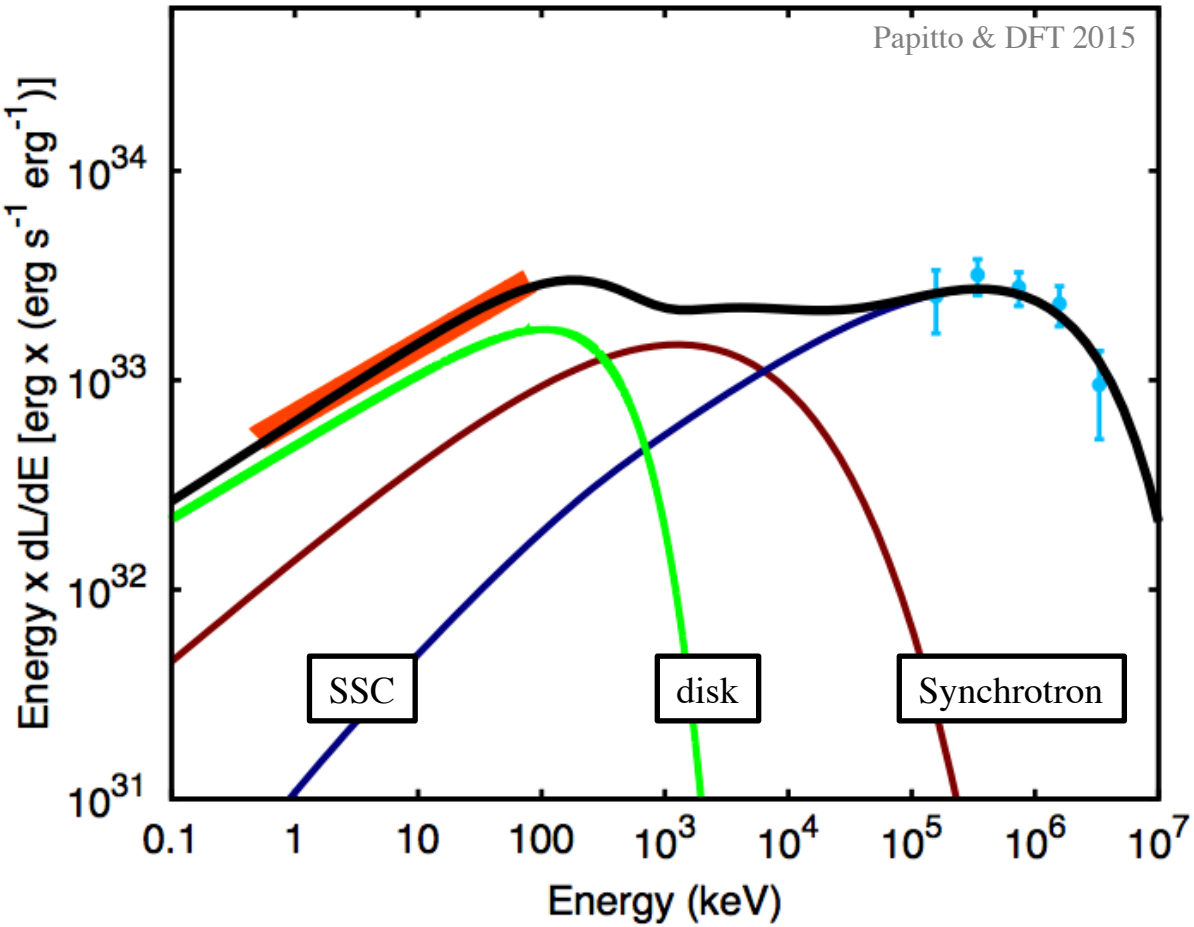
$$L_{prop} = \frac{GM\dot{M}_d}{2R_{\rm in}} [\xi + (\omega_* - 1)^2(1-\beta^2)]$$
$$= 1.75 \times 10^{35}\, \omega_*^{-2/3} [\xi + (\omega_* - 1)^2(1-\beta^2)]\ \mathrm{erg\ s^{-1}}$$



Main ideas

- accretion onto the NS surface is inhibited by the propeller effect (i.e. $R_{lc} > R_{in} > R_c$);
- electrons are accelerated to relativistic energies at the turbulent boundary between the disk and the propelling magnetosphere;
- relativistic electrons interact with the NS magnetic field lines producing synchrotron emission that explains (at least part of) the X-ray emission;
- synchrotron photons are up-scattered by relativistic electrons, to explain the emission observed in the gamma-ray band.

Model results for PSR J1023-0038



$$\frac{dN_e}{d\gamma} \propto \gamma^{-\alpha} \exp\left(-\frac{\gamma}{\gamma_{max}}\right)$$

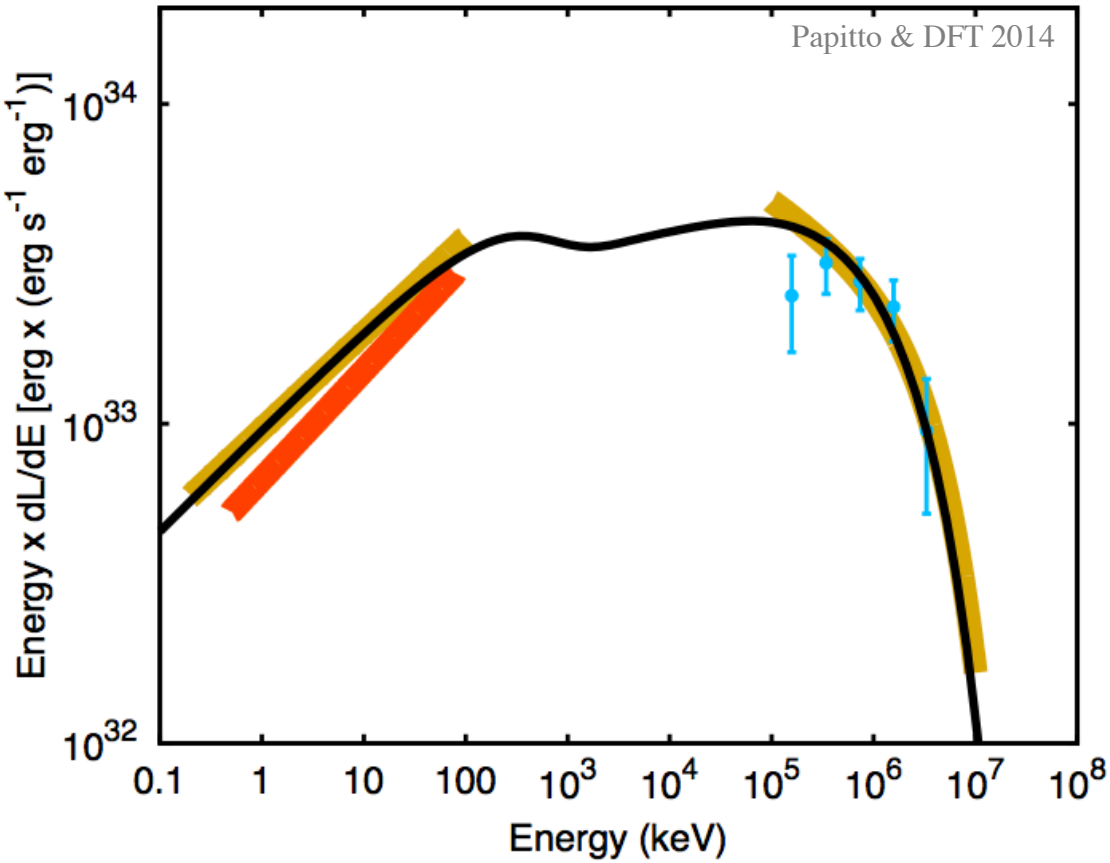
$$\bar{B} = \frac{\mu}{R_{in}^3} = \frac{\mu}{R_c^3 \omega_*^2}$$

Gamma-ray emission dominated by self-synchrotron Compton.

- The parameters of the electron distribution (α, γ_{max}, n_e) and the volume V of the region of acceleration are adjusted to model the gamma-ray emission, for a fixed ω_*.

- The contribution of the disk emission in the X-ray band is modelled as is usual for disks: power-law cut at an energy of a few 100 keV, outside the energy band (we chose 300 keV).

PSR J1023-0038 model compared with XSS J12270-4859 data



For XSS J12270-4859 we assume a distance of 1.4 kpc.

The data similarities suggest that we can also expect a similar magnetic field, and that essentially the same model is a good fit.

Here the model for XSS J12270-4859 SED is obtained for $\xi = 0.15$, $k_{ej} = 0.99$ and $\omega_* = 2.5$

Alternatives to propellering? I.: Accreting scenario

If the observed average X-ray luminosity L_X is ascribed to accretion, the implied mass accretion rate:

$$\dot{M}_{accr} = \frac{\epsilon L_X R}{GM} = 6.2 \times 10^{-13} \times \epsilon^{-1} \frac{L_X}{7.3 \times 10^{33}\,\mathrm{erg\,s^{-1}}} R_{10}\, m_{1.4}^{-1}\, \mathrm{M_\odot\,yr^{-1}}$$

But then, for a mass inflow rate of the order of 10^{-12} solar yr^{-1}, the inner disk radius ~80 km.

Such value clearly violates the criterion for accretion to proceed ($R_{in} < R_c = 24$ km), making the accretion scenario highly unlikely.

Simultaneous observation of a bright gamma-ray emission would be unexplained by the accretion scenario, considering that the transitional pulsars PSR J1023+0038 and XSS J12270-4859 are the only LMXB from which a significant emission could be detected by Fermi/LAT, among a population of > 200 known accreting LMXB.

Alternatives to propellering? II.: binary à la LS 5039?

Is a rotation-powered pulsar active even in the presence of an accretion disk, with the radio coherent pulsation being washed out by the enshrouding of the system by intra-binary material?

Particle acceleration could happen in the shock between the pulsar wind of particles and the mass in-flow (Stappers et al. 2014, Coti-Zelati et al. 2014)

Or directly from interactions of relativistic electrons in the pulsar wind disk photons, with gamma-emission being inverse Compton produced (Takata et al. 2014, Li et al. 2014)

Coherent X-ray pulsation: if not from accretion, the rotationally produced pulsation should be x10 more luminous when the disc is present (extreme mode switching?)

PSR J1023+0038 in X-rays and gamma-rays requires a spin-down power efficiency of ~40%, much larger than the values observed from rotation-powered pulsars, which typically convert 0.1% (X-rays, Vink et al. 2011) and 10% (gamma-rays, Abdo et al. 2013) of their spin down power.

The SED most likely peaks at 1-10 MeV, i.e. if we believe that the X-rays and gamma-rays in the SED are to be modelled by smooth components, a total luminosity equal to ~1.4 L_{sd} is required.

Flickering in X-rays at hundred-s timescales happens already at 40% spin-down. Unless fully anti-correlated with gamma-rays, flaring happens beyond this limit.

Propeller models conclusions

- Provides good fits and is in agreement with the overall MW scenario
- Impossibility of observationally separating contributions just at the X-ray domain, partially limiting model predictability/testing.
- This gives a larger phase space of plausible parameters for the disk component, which can accommodate several different elasticities, radiative efficiencies, etc. (This is good and bad depending how you look)
- Best testeable model predictions happen in a range of energies (few MeV) with no sensitive coverage, or at timescales (<100 s) for which Fermi-LAT is not enough sensitive to track them
- This model predicts no detectable TeV counterparts

Model details in
Papitto & DFT, 2015 ApJ (arXiv 1504.05029)

Parameters (*)

MODEL PARAMETERS USED TO MODEL THE SED OF PSR J1023+0038 AND XSS J12270-4859.

ξ	k_{ej}	ω_*	R_{in} (km)	$\bar{B}$ (MG)	$\dot{M}$	L_{prop}	n_e (10^{18} cm^{-3})	V (10^{15} cm^3)	L_{ssc}/L_{sync}	L^X_{accr}	η^X_{accr}
						PSR J1023+0038					
0.15	0.99	1.50	31.2	2.6	2.7	1.96	54	6×10^{-4}	5.0	0.65	0.06
0.15	0.99	1.75	34.6	1.9	1.9	2.23	10	0.01	2.8	0.59	0.08
0.15	0.99	2.00	37.8	1.5	1.4	2.43	5.0	0.04	2.4	0.55	0.11
0.15	0.99	2.25	40.9	1.15	1.1	2.56	2.1	0.19	2.04	0.51	0.14
0.15	0.99	2.50	43.8	0.94	0.8	2.62	1.3	0.50	1.9	0.48	0.17
						XSS J12270-4859					
0.15	0.99	2.50	43.8	1.34	2.4	2.62	1.7	0.21	2.2	0.55	0.08

NOTE. — Input parameters are listed in the leftmost three columns. Physical quantities obtained using the analytical relations given in text, are listed in columns 4-8. Parameters estimated from the modelling of the observed SED are given in the five rightmost columns. Luminosities are given in units of 10^{34} erg s^{-1}, while the mass in-flow rate is expressed in units of 10^{-11} M$_\odot$ yr^{-1}.