The gamma-ray emission of transitional pulsars

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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?

Accretion and rotation power alternate over timescales as short as few weeks
The three stages of transitional pulsars

**Accretion powered state**
- Bright X-ray outburst ($\sim 10^{36}$ erg/s)
- X-ray pulsations

**An intermediate (propeller?) state**
- Sub-luminous accretion ($\sim 10^{34}$ erg/s)
- Brighter gamma-ray emission

**Rotation powered state**
- Faint in X-rays ($\sim 10^{32}$ erg/s)
- Radio/gamma-ray pulsations
Sub-luminous disk state showed by the transitional PSRs

- **Presence of an accretion disk**, as indicated by 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. 2013)

- **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 \(\Gamma \approx 1.5\) and no cut-off below 100 keV (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);

- **Correlated X-ray/UV emission** on timescales of hundreds of seconds (De Martino et al. 2013);

- **0.1-10 GeV luminosity of \(\approx 10^{34}\) erg s\(^{-1}\)**, ten times brighter with respect to the level observed during the rotation powered state, and not detected by Fermi/LAT from other accreting NS in low-mass X-ray binaries (De Martino et al. 2010; Hill et al. 2011, Papitto, DFT & Li 2014, Stappers et al. 2014; Takata et al. 2014)

- **No pulsations** in the radio, X-ray and gamma-ray band.
Model build up

\[ L_{\text{prop}} + L_{\text{disk}} + \frac{1}{2} \dot{M} v_{\text{out}}^2 = \frac{GM \dot{M}}{R_{\text{in}}} + N \Omega_*, \]

Energy conservation

The energy available to power the radiative emission from the disk, the propeller (inner disk boundary) and the outflow = Gravitational energy liberated by in-fall of matter down to the inner radius, plus the energy release by the magnetosphere through the torque \( N \)
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\]

**Energy conservation**

1. The energy available to power the radiative emission from the disk, the propeller (inner disk boundary) and the outflow.

2. Gravitational energy liberated by in-fall of matter down to the inner radius, plus the energy release by the magnetosphere through the torque \(N\).

\[
L_{disk} = \xi \frac{GMM}{2R_{in}}
\]

The disk luminosity assumed as a fraction of the energy emitted by an optically thick, geometrically thin disk. When \(\xi=1\) the disk is radiatively efficient, lower values indicate that part of the disk energy can be advected.
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   \[ L_{\text{disk}} = \xi \frac{GM\dot{M}}{2R_{\text{in}}} \]

3. Angular momentum conservation at the inner disk boundary:
   \[ \dot{M} R_{\text{in}} v_{\text{out}} = N + \dot{M} \Omega_K R_{\text{in}}^2 \]
   - Rate of angular momentum in the outflow
   - Torque applied by the magnetic field plus angular momentum carried by disk matter

\[ \Omega_K = \sqrt{GM/R_{\text{in}}^3} \]

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These equations can be solved to give $L_{prop}$, once a relation for the velocity of the outflow is assumed.

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

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

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

$\beta$ is the elasticity parameter. Anelastic collision is given by $\beta = 0$. Elastic case is described by $\beta = 1$.

The torque is fixed by the one that the magnetosphere exerts on the disk plasma due to the generation of a poloidal component of the B-field thanks to differential rotation:

$$N = \left(\frac{\Delta r}{R_{in}}\right) \frac{\mu^2}{R_{in}} \left(1 - \frac{1}{\omega_*}\right)$$

Fastness

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

Torque
Relations evaluated for PSR J1023+0038 ($\mu = 0.79 \times 10^{26}$ G cm$^3$, $M = 1.4$ $M_\odot$, $R_c = 23.8$ km), for the case of an efficiently radiative disk ($\xi = 1$), anelastic collision ($\beta = 0$) at the magnetospheric boundary, and setting the turbulence region size as $\Delta r / R_{in} = 0.5$.

For $\omega_\ast \geq 2$ the energy liberated by the propelling magnetosphere becomes larger than the disk contribution.
The parameters of the electron distribution \((\alpha, \gamma_{\text{max}}, n_e)\) and the volume \(V\) of the region of acceleration are adjusted to model the gamma-ray emission, for a fixed \(\omega_s\).

The contribution of the disk emission in the X-ray band is modelled as a power-law cut-off at an energy outside the energy band (we chose 300 keV).

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

\[
\bar{B} = \frac{\mu}{R_{\text{in}}^3} = \frac{\mu}{R_c^3 \omega_s^2}
\]

Gamma-ray emission dominated by self-synchrotron Compton.
For XSS J12270-4859 we assume a distance of 1.4 kpc.

Its spin period is \( \sim 1.7 \) ms, but its period derivative is unknown.

The data similarities suggest that we can also expect a similar magnetic field, and that essentially the same model is a good fit.
Alternatives to propelling? I.: Accreting scenario

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

$$\dot{M}_{\text{acrr}} = \frac{\epsilon L_X R}{GM} = 6.2 \times 10^{-13} \times$$

$$\epsilon^{-1} \frac{L_X}{7.3 \times 10^{33} \text{erg s}^{-1}} \frac{R_{10} m_{1.4}^{-1}}{\text{M}_\odot \text{yr}^{-1}}$$

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

Such value clearly violates the criterion for accretion to proceed ($R_{\text{in}} < R_c = 24$ 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 transitonal 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? (Stappers et al. 2014, Takata et al. 2014)

Particle acceleration could happen in the shock between the pulsar wind of particles and the mass in-flow (Stappers 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)

The brightness of PSR J1023+0038 observed in X-rays and gamma-rays requires a spin-down power conversion 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.

Variability in X-rays?
Propeller models caveats

• 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 testable model predictions happen in a range of energies with no sensitive coverage, or at timescales for which Fermi-LAT is not enough sensitive to track them

• Swings of mass accretion by a factor of ~3-4 around average can account for X-ray variability, although the largest mass accretion can formally yield to accretion radius lower than co-rotation. Is there partial accretion at the peak of the flares?

• (Note that this model predicts no detectable TeV counterparts)
What drives variations of the mass in-flow rate?
    Tidal interactions? Mass accumulation?

How efficient is the propeller?

Outflows during accretion powered stage
    (radio/X-ray correlations)?

Are all millisecond pulsars in close binary systems transitional? Where are the others?
    (see Papitto, DFT, Rea, Tauris 2014)
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