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Accretion and rotation-powered pulsars, two distinct classes?

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Abstract. A long-standing paradigm assumes that a pulsar in a binary system is not observed as a radio/gamma-ray pulsar powered by its rotation as long as matter flows towards the neutron star in an accretion disk. Hence millisecond pulsars are assumed to turn on as radio/gamma-ray sources only after the end of the Gyr-long, X-ray bright phase of accretion of matter from a low mass companion star that spun them up. Transitional millisecond pulsars challenge this picture, as they swing between an accretion-powered X-ray pulsar regime and a rotationally-powered radio pulsar state in a few weeks or even less. The incredibly rich phenomenology of transitional pulsars reflects all the possible outcomes of the interaction between the pulsar wind of particles and radiation and matter in an accretion disk. In this context, the recent discovery of optical pulsations from a transitional millisecond pulsar indicated that a rotation-powered magnetospheric process can be active even when the pulsar is surrounded by an accretion disk. This suggests that the dichotomy between accretion and rotation-powered pulsars might be even less pronounced than commonly thought.

Key words. Stars: neutron – Stars: pulsars

1. Introduction

The rotation of the neutron star (NS hereafter) magnetic field and the accretion of matter transferred by a companion star are by far the most common mechanisms powering pulsars. We currently know more than 2700 rotation-powered pulsars observed mainly in the radio[1] and gamma-ray bands (∼ 300 of which in binary systems, Manchester et al. 2005), and more than two hundreds accreting X-ray pulsars in binary systems[2].

The evolutionary link between pulsars powered by these two regimes is evident in the case of millisecond pulsars. They attain their short spin period during a Gyr-long evolutionary phase during which they accrete matter transferred by a low mass ($\leq M_{\odot}$) companion star in a binary system and shine as a bright X-ray source. The ∼ ms radio pulsars (MSP) in our Galaxy are consequently believed to be the recycled descendants of accreting NS in low mass X-ray binaries (NS-LMXB). A long standing paradigm states that when the NS magnetosphere is engulfed by in-flowing plasma, vacuum gaps in the magnetosphere are readily filled and acceleration of electron/positron pairs in the magnetosphere cannot occur (Shvartsman 1971). Only when

[1] http://www.atnf.csiro.au/research/pulsar/psrcat

[2] http://www.iasfbo.inaf.it/~mauro/pulsar_list.html

mass transfer stops and the magnetosphere is not filled by mass transferred from the donor anymore, a radio/gamma-ray pulsar powered by the rotation of the NS magnetic field is then assumed to possibly switch on (Alpar et al. 1982). So far, observations have also confirmed that a millisecond pulsar in a binary system is either observed as an accretion or as a rotation-powered pulsar.

The three transitional millisecond pulsars recently discovered (Archibald et al. 2009; Papitto et al. 2013; Bassa et al. 2014) showed an incredibly rich and complex phenomenology which has challenged this simple picture. These pulsars swing between a rotation-powered radio pulsar regime and a state in which an accretion disk forms and the X-ray emission brightens. Changes of state take place over less than a couple of weeks, compatible with the typical time-scales of the variations of the mass accretion rate of the neutron star.

At low mass in-flow rates ($L_X \leq 10^{32}$ ergs^{-1}), transitional millisecond pulsars behave as redback radio pulsars (D'Amico et al. 2001; Strader et al. 2019); the pressure exerted by their relativistic wind prevents matter transferred from the donor from forming an accretion disk and ejects it from the system. Such a plasma is responsible for the irregular eclipses of the radio pulsed signal observed preferentially when the donor is at the inferior conjunction of the orbit. At a higher mass transfer rate a disk forms, the magnetosphere is squeezed to a size of a few tens of km and relatively bright X-ray emission is observed. The transitional pulsar IGR J18245-2452 showed in 2013 a bright X-ray outburst ($L_X \geq 10^{36}$ ergs^{-1}) first spotted by INTEGRAL; X-ray pulsations due to magnetic channelling of the accretion in-flow were detected at the 3.9 ms period of the pulsar by XMM-Newton (Papitto et al. 2013). The pulsation properties as well as the X-ray spectrum of the source were very similar to accreting millisecond pulsars (see, e.g., Patruno & Watts 2012), although extreme variability characterised the X-ray light curve (Ferrigno et al. 2014). On the other hand, the accretion disk state of the two other confirmed transitional millisecond pulsars, PSR J1023+0038 and XSS J12270-4859, turned out to be a peculiar and X-ray *sub-luminous* (Patruno et al. 2014). Remarkably, a similar regime was observed also in archival observations of IGR J18245-2452 (Papitto et al. 2013; Linares 2014), as well as from a number of binary systems which for this reason have been identified as transitional ms pulsars (Bogdanov & Halpern 2015; Coti Zelati et al. 2019). Fitting the complex multi-wavelength phenomenology of this X-ray *sub-luminous* disk state is one of the main tasks of current studies of transitional millisecond pulsars, as it could possibly unveil a previously unseen outcome of the pulsar wind-disk interaction.

2. The X-ray *sub-luminous* disk state of transitional ms pulsars

The non-detection of radio pulses, the observation of broad, double peaked emission lines of the Balmer series of Hydrogen in optical spectra and a brightening of the X-ray emission are the main hallmarks of a transition of a millisecond pulsar to the accretion regime (Stappers et al. 2014; Patruno et al. 2014). The X-ray *sub-luminous* accretion disk state of transitional millisecond pulsars is very different than the outbursts of accreting ms pulsars (such as that shown by IGR J18245-2452 in 2013) and in general of transient NS-LMXBs. The X-ray luminosity is much lower, $L_X \simeq$ a few $\times 10^{33}$ ergs^{-1}, i.e. $\sim 10^{-5}$ times the Eddington rate. Transitional ms pulsars can persist in this stage for a decade (Papitto et al. 2014), i.e. for timescales which are much longer than the typical few weeks-long outbursts of accreting ms pulsars. Most strikingly, every time a transitional ms pulsars is observed in the *sub-luminous* accretion disk state, the X-ray light curve shows a distinctive variability between a *high* and a *low* mode, each characterised by a remarkably constant flux. Transitions between these modes suddenly take place on $\sim$ 10 s timescale (see Fig.1). X-ray Flares are also observed. X-ray pulsations are observed with an rms amplitude of 8 – 10% during the *high* mode, and disappear in the *low* mode (Archibald et al. 2015; Papitto et al. 2015). The similarities of the pulse properties with those of accreting ms pulsars led these authors to interpret them in terms of magnetic channelling of the accretion flow towards the polar caps on the neutron star surface. However, such an interpretation is troublesome as the X-ray luminosity at which pulsations are observed is very low and would make transitional millisecond pulsars in the *sub-luminous* disk state the faintest accretion-powered pulsar know; at such an X-ray luminosity, a quickly spinning neutron star is in fact expected to propel away most of the incoming matter. To circumvent this problem (Papitto et al. 2014) and (Papitto & Torres 2015) proposed that these transitional ms pulsars lied in a propeller state in which the rotating magnetosphere ejected most of the disk matter from the inner disk radius, assumed to be located at a few times the co-rotation radius (≃25 km for PSR J1023+0038 and XSS J12270-4859).

The multi-wavelength phenomenology of the *sub-luminous* disk state of transitional ms pulsars is also extremely rich and complex. Unpulsed continuous radio emission is observed at a flux density that exceeds what is predicted for accreting NS at the given X-ray luminosity, and is close to the values rather expected for accreting black holes (Deller et al. 2013). The flat or slightly inverted average spectrum suggested an origin in a compact jet of relativistic particles. Bursts of radio emission are also seen during the X-ray *low* mode, possibly due to the ejection of optically thin plasmoids (Bogdanov et al. 2018).

Strikingly, the Fermi Large Area Telescope showed that the GeV gamma-ray emission of transitional ms pulsars in the *sub-luminous* disk state brightens by a factor of a few than in the radio pulsar state (de Martino et al. 2010; Stappers et al. 2014). Transitional ms pulsars are indeed the first low mass X-ray binaries to be detected as GeV emitters. In the disk state the 0.1–10 GeV flux becomes comparable to that observed in 0.1–10 keV X-ray band, while the spectrum is cut-off at a few GeVs similar to what is seen during the radio pulsar phase (Torres et al. 2017). Coti Zelati et al. (2014) and Takata et al. (2014) first interpreted the increased gamma-ray emission observed in the *sub-luminous* disk state as an indication of the formation of a shock between the disk plasma and the pulsar wind far from the NS ($R \sim 10^{9-10}$ cm). According to these models a rotation-powered pulsar would be active in the system regardless of the presence of an accretion disk. The observation of X-ray pulsations with a pulsed flux ~25 times larger than during the radio pulsar regime would not find an immediate explanation, though (but see below). Alternatively, (Papitto et al. 2014; Papitto & Torres 2015) proposed that particle were accelerated in a shock located at the boundary between the disk and a propellering magnetosphere, i.e. a few times the co-rotation radius. There, synchrotron and self-synchrotron Compton emission would account for the emission observed in the X-ray and gamma-ray band, respectively.

2.1. Discovery of optical pulsations

The bulk of the optical emission of transitional ms pulsars is due to intrinsic and reprocessed emission from outer rings of the accretion disk and the surface of the companion star facing the pulsar. Variability both on the orbital (a few hours) and longer (days) timescales is observed, together with flares occurring simultaneously to X-ray flares (Shahbaz et al. 2015; Kennedy et al. 2018; Papitto et al. 2018; Shahbaz et al. 2018). Polarization up to a few per cent is detected both in the optical (Baglio et al. 2016) and in the near infrared band (Hakala & Kajava 2018).

To investigate the fast variability properties of the optical emission, Ambrosino, Papitto et al. (2017) observed PSR J1023+0038 at the 3.6 m INAF Galileo Telescope (TNG, hereafter) equipped with the photometer SiFAP, a Si photo-multiplier capable of tagging individual optical photons with an relative accuracy $< \mu$s and absolute accuracy $< 60\mu$s (Ambrosino et al. 2016). Observations performed in March 2016 revealed a coherent signal at the pulsar spin period with an rms amplitude of 0.5–1%, making PSR J1023+0038 the first optical millisecond pulsar ever detected. The pulse period was modulated by the orbital Rømer effect with the same orbital parameters measured from the radio and X-ray pulsations.

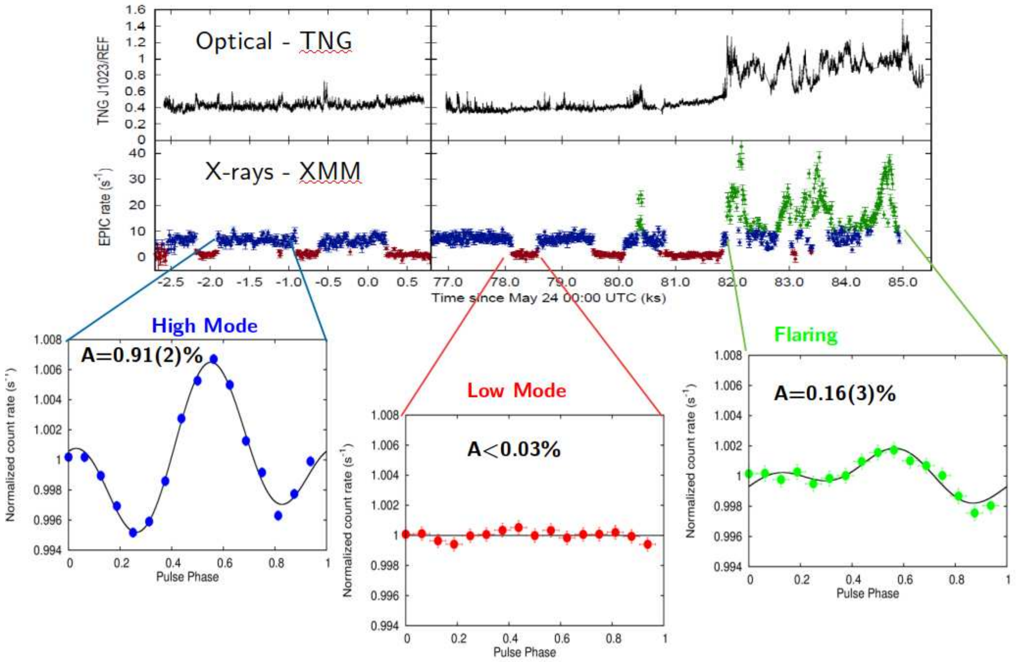

Fig. 1. The top panel shows the *SiFAP/TNG* optical and *XMM-Newton* X-ray light curves of PSR J1023+0038 during simultaneous observations performed on 2017, May 23 and 24 (Papitto et al. 2019). Blue, red and green points in the X-ray light curve mark the *high*, *low* and *flaring* modes of PSR J1023+0038. The insets show the optical pulsations observed by *SiFAP/TNG* in the three modes.

The source of optical pulses had then to lie at most within a few tens of kilometres from the pulsar, ruling out irradiation of the outer disk or the companion star. The 320-900 nm pulsed luminosity attained a value as high as 10^{31} erg s^{-1}, i.e. 10^{-4} times the spin down power of PSR J1023+0038. Such a luminosity exceeds by ~ 35 times the value expected if optical pulses were due to optically thick cyclotron emission by $\sim$ 100 keV electrons in the accretion column of a pulsar with 10^8 G magnetic field and hot spot size of ~ 100 km^2. Channelled accretion is then unlikely the driver of optical pulsations.

A rotation-powered pulsar is an intriguing alternative to explain optical pulses. Five younger and slower optical pulsars are known (Mignani 2011), like the Crab and the Vela pulsar. Their optical pulsations are ascribed to synchrotron emission of $\sim$ 100 MeV electrons accelerated in magnetospheric vaccum gaps. Continued activity of a rotation-powered pulsars in PSR J1023+0038 would also help to explain why the spin-down rate of the pulsar increased by just 26% with respect to the radio-pulsar regime (Jaodand et al. 2016), as accretion torques are expected to produce a much faster spin evolution. Notably, if it is active as a rotation-powered pulsar, PSR J1023+0038 would be more efficient in producing optical pulses than these isolated pulsars, as its pulsed flux is $\approx 2.5\times10^{-4}$ times the spin down energy, a value larger than what is found even for the Crab pulsar ($\approx 10^{-5}$). Interaction of the pulsar wind with the accretion disk represents a possible mechanism to justify such an increased efficiency.

This suggestion is also supported by simultaneous optical/X-ray observations performed in 2017, May by the TNG and XMM-Newton, respectively (Papitto et al. 2019). Optical and X-ray pulses were observed in the X-ray *high* mode, while they were both undetected in the X-ray *low* mode (see Fig. 1). Pulses detected in the two bands were both described by two sinusoidal harmonics with comparable amplitude.

The optical pulses lagged the X-ray pulses by $\sim 200\,\mu$s, a measure affected by a systematic uncertainty of $\sim 100\,\mu$s. More recent observations performed with detectors with a negligible absolute time uncertainty, such as *NICER* and *Aqueye+* (Zampieri et al. 2019), confirmed the lag. The pulsed optical flux density is also compatible with the continuation of the $F_\nu \propto \nu^{-0.7}$ power law that describes the X-ray pulsed flux observed by XMM-Newton and NuSTAR. All these observations strongly point to a single mechanism as the driver of optical and X-ray pulses. As the energy budget of cyclotron emission in the accretion column is not sufficient to explain optical pulses, also the accretion interpretation of X-ray pulses should be probably revised. A magnetospheric rotation-powered mechanism would require an unusually high efficiency in converting the spin down power into optical and X-ray pulsations. To overcome these difficulties, we proposed that the accretion in-flow could be blocked by the relativistic wind of a rotation-powered pulsar $\sim 1-2$ light cylinder radii, i.e., $\sim 100-200$ km away from the pulsar. There the wind is magnetically dominated and has a striped structure.

The pulsar wind is then expected to deposit energy in the shock every spin period. If this energy is used to accelerate particles, synchrotron emission would produce the observed pulsations. The synchrotron timescales are small enough to ensure that energy is radiated away before a new crest of the wind flows through the shock, and would also provide a plausible explanation of the observed lag of the optical pulses.

Transition to the X-ray *low* mode and simultaneous disappearance of pulsations would be explained if the shock interface gets farther from the pulsar, a smaller fraction of the spin down power is seen by the shock and converted into radiation, and the size of the shock becomes too large to produce coherent pulsations. Future observations and modelling will test the hypothesis that transitional ms pulsars in the X-ray *sub-luminous* disk state host a dwarf ($\sim 100-200$ km) pulsar wind nebula contained by the accretion flow.

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