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The ms pulsar - low mass X-ray binary link

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Abstract. The recent discovery of a binary millisecond pulsar in the globular cluster M28 that switched between an X-ray pulsar and a radio pulsar state demonstrated the tight link shared by millisecond pulsars and their accreting low-mass X-ray binary progenitors. This pulsar is the prototype of a new class of transitional systems that alternate between accretion and rotation-powered states in response to variations of the rate of mass in-flow, on time scales possibly shorter than a couple of weeks. Observations of this and other similar systems indicate that transitions to the accretion phase not only involve bright X-ray outbursts, but also an X-ray *sub-luminous* accretion disk state, possibly characterized by centrifugal inhibition of the matter in-flow. The main observed properties of the known *transitional* ms pulsars, as well as the prospects of finding more sources of this newly established class, are summarized here.

Key words. accretion, accretion disks – magnetic fields – pulsars – X-rays: binaries

1. Introduction

The short spin periods of ms pulsars are the outcome of the accretion of the mass transferred by a low mass ($\lesssim M_\odot$) companion star through an accretion disk. This evolutionary scenario is known as the recycling of old neutron stars (NSs) in binaries (Alpar et al. 1982). After a Gyr-long, X-ray bright accretion disk phase, the mass transfer rate declines and allows the activation of a pulsar powered by the rotation of its magnetic field, emitting from the radio to the gamma-ray band. The ~300 ms radio pulsars (MSPs) in our Galaxy are believed to be the recycled descendants of accreting NS in low mass X-ray binaries (NS-LMXBs).

While the discovery of ms pulsations from accreting NS (accreting ms pulsars, AMSPs, Wijnands & van der Klis 1998; Patruno & Watts 2012), showed that accretion is able of spinning up a NS to such a short period, it was only thanks to the recent discovery of swings between accretion and rotation-powered emission by three *transitional* ms pulsars that the tight link shared by MSPs and NS-LMXBs could be finally proven.

2. IGR J18245–2452

The globular cluster M28 hosts 46 X-ray sources (Becker et al. 2003) and 12 ms pulsars (Bogdanov et al. 2011), the third largest population of pulsars in a globular cluster.

The transient X-ray source IGR J18245–2452 was discovered during an accretion outburst that took place in March 2013, when it reached an X-ray luminosity of $L_X \gtrsim 10^{36}$ erg s^{-1}. Accretion-powered pulsations at a period of 3.9 ms were discovered in the X-ray emission observed by XMM-Newton (Papitto et al. 2013). The pulsar is in a 11 hr-orbit around a companion with a mass larger than 0.17 $M_{\odot}$. Cross-referencing with pulsar catalogs, it was realized that the source behaved as a rotation powered radio pulsar a few years before, indicating that it performed a transition between rotation and accretion-powered activity (Papitto et al. 2013).

The state transitions happened on a short time scale, compatible with variations of the mass accretion rate onto the NS. At a high accretion rate the magnetosphere was squeezed to a size of few tens of km, a bright ($L_X \approx 10^{36}$ erg s^{-1}) X-ray outburst took place, and X-ray pulsations were seen as matter was channeled onto the NS magnetic poles. As the outburst faded ($L_X \lesssim 10^{32}$ erg s^{-1}), the magnetosphere expanded up to the light cylinder ($\approx$ 300 km) and reactivated a radio pulsar, which was detected less than two weeks since the end of the outburst. Archival optical and X-ray observations revealed two more faint accretion events in five years (Papitto et al. 2013; Pallanca et al. 2013; Linares et al. 2014), giving a recurrence time typical of X-ray transients.

The X-ray light curve of IGR J18245–2452 during the outburst was also highly peculiar. The flux varied by more than two orders of magnitudes on time scales shorter than a second, sometimes coupled to a hardening of the X-ray spectral distribution. Ferrigno et al. (2014) attributed this phenomenology to partial centrifugal inhibition of accretion, expected when the accretion disk recedes and the rotation of the disk plasma becomes slower than the magnetospheric field lines (i.e., the propeller effect, Illarionov & Sunyaev 1975).

3. PSR J1023+0038

PSR J1023+0038 was discovered in 2009 as a 1.7 ms radio pulsar positionally coincident with a source that had an accretion disk in 2000/2001 (Archibald et al. 2009). The presence of a disk was deduced thanks to the observation in the optical spectrum of double peaked hydrogen emission lines, that subsequently disappeared when the source was detected a radio pulsar (Wang et al. 2009). In June 2013, the source entered into a new accretion disk state (dubbed *sub-luminous*), characterized by a relatively faint, variable X-ray emission ($L_X \simeq 2 \times 10^{33}$ erg s^{-1}; Patruno et al. 2014; Tendulkar et al. 2014; Bogdanov et al. 2015), pulsed at the spin period of the NS (Archibald et al. 2015), by a bright unpulsed radio emission with a flat spectrum (Deller et al. 2015), and by a gamma-ray emission of roughly the same magnitude of the X-ray flux, and $\sim$ 5 times larger than the one observed during the radio pulsar state (Stappers et al. 2014).

4. XSS J12270-4859

XSS J12270-4859 is a low-mass X-ray binary that stayed for a decade in a sub-luminous disk accretion phase (de Martino et al. 2010, 2013), during which it emitted a faint, pulsed X-ray emission ($L_X \simeq$ few $\times 10^{33}$ erg s^{-1}; Papitto et al. 2015), and was positionally associated with a Fermi/LAT, and a flat spectrum radio source (de Martino et al. 2010; Hill et al. 2011). In December 2012 the disk disappeared (Bassa et al. 2014), the source dimmed in optical, X-rays and gamma-rays (Bogdanov et al. 2014; de Martino et al. 2015), and a 1.7 ms radio (Roy et al. 2014), and gamma-ray pulsar (Johnson et al. 2015) turned on.

5. The sub-luminous disk state

One of the main questions opened by the discovery of transitional ms pulsars regards the mechanism powering their emission in the sub-luminous disk state. The observation of an enhanced emission at GeV energies led Takata et al. (2014) to argue that a rotation-powered pulsar is active in this state, in spite of the presence of the disk (see also Coti Zelati et al. 2014). Gamma-rays would be due to magnetospheric emission and to up-scattering of disk photons off the relativistic charges of the pulsar wind. X-rays would originate at the shock created by the interaction between the pulsar wind and the disk truncated outside the light cylinder.

However, the detection of X-ray pulsation most likely powered by the accretion of matter onto the NS surface from two transitional ms pulsars (Archibald et al. 2015; Papitto et al. 2015) argued against the hypothesis that a radio pulsar is permanently turned on in the sub-luminous disk state. In fact, the presence of high density plasma inside the pulsar light cylinder is expected to poison magnetospheric vacuum gaps, and prevent acceleration of electrons and positrons to relativistic energies. At the same time, the low X-ray luminosity at which pulsations were observed raised the problem of how the accretion disk could be kept close to the co-rotation boundary, in order to avoid complete inhibition of the accretion down to the NS surface due to the centrifugal repulsion exerted by the rotating pulsar magnetosphere. Papitto et al. (2014a) and Papitto & Torres (2015) interpreted the high energy emission as due to a propelling pulsar than truncates the accretion disk just outside the co-rotation radius and ejects away most of the disk matter. Assuming that electrons and positrons can be accelerated to relativistic energies at the turbulent disk-magnetospheric boundary, synchrotron and self-synchrotron Compton emission would then contribute to most of the emission observed in the X-ray and gamma-ray bands, respectively. The observation of a flat radio spectrum, typically considered as a signature of jets in accreting compact objects, supports the hypothesis that large mass outflows can be launched by these pulsars. Alternatively, a propeller ejection of mass may not be realized at all even if the disk is truncated beyond the co-rotation boundary. The disk gas could remain trapped near co-rotation thus providing the inward pressure required to keep the disk close to the neutron star in spite of the low mass accretion rate (D'Angelo & Spruit 2012). A measure of the spin evolution of these pulsars in the sub-luminous disk state (Jaodand et al. in prep.) will help to shed light on the physical mechanisms at work.

6. Candidate transitional ms pulsars

In the sub-luminous accretion disk state all the transitional ms pulsars are highly peculiar as they show a faint and variable X-ray light curve, correlated optical and UV flares, and a bright and variable output in the radio and gamma-ray bands. Based on these peculiarities, Bogdanov & Halpern (2015) identified 3FGL J1544.6-1125 as a very promising candidate transitional pulsar, even if pulsations have not been detected, so far.

It is often assumed that a binary MSP will possibly turn on as an accreting source only if its companion star is almost filling its Roche lobe, and currently transferring mass. The radius of the donor is in fact expected to vary over much longer time scales (> 50 Myr; Tauris et al. 2012) than those observed. MSPs that might perform a transition to an accretion stage are then being searched among those showing indication of an interaction between the pulsar wind and the mass lost from the donor. A useful tracer of such an interaction is the observation of irregular eclipses of the radio signal due to free-free absorption of matter ejected by the outward pressure of the radio pulsar wind and enshrouding the system. Eclipsing pulsars are dubbed black widows (BWs, $M_c << 0.1\,M_\odot$; Fruchter et al. 1988) or redbacks (RBs, $M_c \simeq 0.2-0.4\,M_\odot$; D'Amico et al. 2001). Currently, ≈ 60 sources belonging to these classes are known, roughly half of which lie in globular clusters, and all in $P_{orb} < 1$ day binaries (see Fig. 1 and Roberts et al. 2013). Most notably, all the transitional ms pulsars discovered so far are redbacks. Detecting state transitions from more MSPs will help us understanding if the transitional behavior is restricted to a certain range of orbital periods and mass of the companion, and only to some evolutionary channels. In this context, optical, X-ray and gamma-ray monitoring programs of RBs and BWs are currently ongoing, aimed at detecting the brightening associated to a switch to the accretion state.

On the other hand, it was proposed that all the transiently accreting AMSPs might turn on as radio pulsars during the years-long period of X-ray quiescence (Stella et al. 1994; Campana et al. 1998; Burderi et al. 2001). Irradiation by the pulsar wind would provide a powerful enough irradiation of the donor star to explain the large optical brightness observed from AMSPs in quiescence (Burderi et al. 2003). In addition, the spin and orbital period evolution of AMSPs in quiescence closely resembles that observed from BWs and RBs (Hartman et al. 2008; Patruno et al. 2012). The non-detection of radio pulsations from the

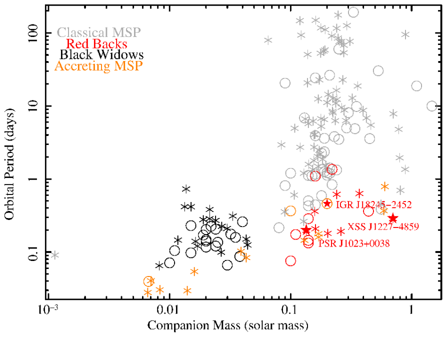

Fig. 1. Orbital period and minimum mass of the donor star of classical MSP with a white dwarf companion (gray), black widows (black), redbacks (red), and accreting ms pulsars (orange). Asterisks and circles mark sources in the Galactic field and in globular clusters, respectively.

majority of AMSPs could be related to their distance and/or to absorption of the radio emission by matter enshrouding the binary system. Absorption does not affect the gamma-ray emission though, and recently, a Fermi/LAT gamma-ray counterpart has been proposed for the AMSP SAX J1808.4–3658 in quiescence (Xing et al. 2015; de Oña Wilhelmi et al. 2016), even if pulsations could not be detected due to low counting statistics. The similarity of the spin period distribution (Papitto et al. 2014b) and orbital characteristics (see Fig. 1) of AMSPs, BWs and RBs, further strengthens the indication that these sources might belong to a unique class of systems at the brink between accretion and rotation-powered activity.

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