Chapter 4
Accreting Pulsars: Mixing-up Accretion Phases in Transitional Systems

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Abstract In the last 20 years our understanding of the millisecond pulsar population changed dramatically. Thanks to the large effective area and good time resolution of the NASA X-ray observatory Rossi X-ray Timing Explorer, we discovered that neutron stars in Low Mass X-ray Binaries (LMXBs) spins at frequencies between 200 and 750 Hz, and indirectly confirmed the recycling scenario, according to which neutron stars are spun up to millisecond periods during the LMXB-phase. In the meantime, the continuous discovery of rotation-powered millisecond pulsars in binary systems in the radio and gamma-ray band (mainly with the Fermi Large Area Telescope) allowed us to classify these sources into two “spiders” populations, depending on the mass of their companion stars: Black Widow pulsars, with very low-mass companion stars, and Redbacks, with larger mass companion stars possibly filling their Roche lobes without accretion of matter onto the neutron star. It was soon regained that millisecond pulsars in short orbital period LMXBs are the progenitors of the spider populations of rotation-powered millisecond pulsars, although a direct link between accretion-powered and rotation-powered millisecond pulsars was still missing. In 2013 the ESA X-ray observatory XMM-Newton spotted the X-ray outburst of a new accreting millisecond pulsar (IGR J18245−2452) in a source that was previously classified as a radio millisecond pulsar, probably of the Redback type. Follow up observations of the source when it went back to X-ray quiescence showed that it was able to swing between accretion-powered to rotation-powered pulsations in a relatively short timescale (few days), promoting this source as the direct link between the LMXB and the radio millisecond pulsar phases. Following discoveries showed that there exists a bunch of sources which alternates X-ray activity phases, showing X-ray coherent pulsations, to radio-loud phases,

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showing radio pulsations, establishing a new class of millisecond pulsars, the so-called transitional millisecond pulsars. In this review we describe these exciting discoveries and the properties of accreting and transitional millisecond pulsars, highlighting what we know and what we have still to learn about in order to fully understand the (sometime puzzling) behaviour of these systems and their evolutive connection.

4.1 The Links in the Chain: How a Neutron Star Becomes a Millisecond Pulsar

4.1.1 The Recycling Scenario: The Evolutionary Path Leading to the Formation of Millisecond Pulsars

A millisecond pulsar (hereafter MSP) is a fast rotating, weakly magnetised neutron star. A weak magnetic field for a neutron star means a magnetic field of $\sim 10^7$–10^8 G, that is several orders of magnitude higher than the strongest magnetic fields that can be produced on Earth laboratories (the highest magnetic field strength created on Earth is $\sim 9 \times 10^5$ G[1]), but weak with respect to the magnetic field of a newly born neutron star (which is $\gtrsim 10^{11}$–10^{12} G). MSPs have spin periods in the range 1–10 ms, corresponding to spin frequencies above 100 Hz. MSPs were first discovered in the radio band, with the detection of periodic radio pulses. The first discovered MSP is PSR B1937+21 (Backer et al. 1982), spinning roughly 641 times a second; this is to date the second fastest-spinning MSP among the ~300 that have been discovered so far. PSR J1748−2446ad, discovered in 2005 (Hessels et al. 2006), is the fastest-spinning pulsar currently known, spinning at 716 Hz. These millisecond spinning neutron stars are extreme physical objects: general and special relativity are fully in action, since their surfaces, attaining speeds close to one fifth of the speed of light, are located extremely close to their Schwarzschild radius. In addition electro-dynamical forces, caused by the presence of huge surface magnetic fields of several hundred million Gauss, display their spectacular properties accelerating electrons up to such energies to promote pair creation in a cascade process responsible for the emission in the radio and γ-ray bands. The rotational energy is swiftly converted and released into electromagnetic power which, in some cases, causes the neutron star to outshine with a luminosity of hundreds Suns.

Standard radio pulsars are usually isolated objects, with relatively high magnetic field strengths ($\gtrsim 10^{11}$ G) and relatively long spin periods ($\gtrsim 0.1$ s). Neutron star magnetic fields are probably the relic magnetic field of the progenitor star that is enhanced by "flux freezing", or conservation of the original magnetic flux, when the core of the progenitor star collapses to form a neutron star. Moreover, as the core of a massive star ($\geq 8\,M_\odot$) is compressed and collapses into a neutron star, it

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[1] https://phys.org/news/2011-06-world-strongest-magnetic-fields.html.

retains most of its angular momentum. But, because it has only a tiny fraction of the radius of its progenitor star, a neutron star is formed with very high rotation speed. An interesting example of a recently formed pulsar is the Crab pulsar, the central star in the Crab Nebula, a remnant of the supernova SN 1054, which exploded in the year 1054, less than a thousand years ago, that shows a spin period of 33 ms and a magnetic field strength of $B \gtrsim 4 \times 10^{12}$ G.

The strong magnetic field of the newly born neutron star and the high rotational velocity at its surface generate a strong Lorentz force resulting in the acceleration of protons and electrons on the star surface and the creation of an electromagnetic beam emanating from the poles of the magnetic field, which is responsible for the observed pulsed emission. In rotation-powered pulsars, the energy of the beam comes from the rotational energy of the pulsar, which therefore starts to spin-down. At zero-order the pulsar behaves as a rotating magnetic dipole which emits energy according to the Larmor formula (see Jackson's Classical Electrodynamics):

$$P_{\rm rad} = \frac{2}{3}\frac{(\ddot{m}_\perp)^2}{c^3} = \frac{2}{3}\frac{m_\perp^2 \Omega^4}{c^3} = \frac{2}{3c^3}(BR^3 \sin\alpha)^2 \left(\frac{2\pi}{P}\right)^4 , \tag{4.1}$$

where $m_\perp = BR^3 \sin\alpha$ is the component of the magnetic dipole moment perpendicular to the rotation axis, B and R are the surface magnetic field and the neutron star radius, respectively, α is the angle between the rotation axis and the magnetic dipole axis, Ω is the spin angular frequency of the neutron star and P its spin period. The pulsar, therefore, gradually slows down at a rate that is higher for stronger magnetic fields and faster spins. If the magnetic field strength does not change significantly with time, we can estimate a pulsar's age from its spin period and the spin-down rate, by assuming that the pulsar's initial period P_0 was much shorter than the current period:

$$\tau \equiv \frac{P}{2\dot{P}} . \tag{4.2}$$

This is the timescale necessary to bring the pulsar from its initial spin period P_0 to its actual period at the observed spin-down rate, and is called characteristic age of the pulsar. Indeed the characteristic age of the Crab is ~2.5 kyr.

Soon after their discovery it became clear that MSPs are old neutron stars, with relatively weak magnetic fields, of characteristic ages comparable to the age of the Universe; these were therefore recognised as a different class of objects, called *recycled pulsars*. Binary systems that can host an old neutron star and may be responsible for the recycling are the so-called Low Mass X-ray Binaries (hereafter LMXBs), in which an old, weakly magnetised, neutron star accretes matter from a low-mass (less that 1 $M_\odot$) companion star. In these systems, matter transferred from the companion star enters the Roche lobe of the neutron star through the inner Lagrangian point and releases a large amount of gravitational energy before falling onto the neutron star. These systems may be up to five orders of magnitude more luminous than the Sun, and the temperature matter reaches close to the neutron star ranges from few keV up to a hundred keV, making these systems the brightest Galactic sources in the X-ray band. Because of the small size of the companion star, these systems are also quite compact, with orbital periods ranging from several minutes up to one day. For this reason, matter leaving the companion star, has a high specific angular momentum and cannot fall directly onto the neutron star. Besides an accretion disc is formed, where matter rotates with Keplerian velocities and looses energy until it reaches the innermost part of the system, close to the neutron star. When this matter accretes onto the neutron star surface it has relativistic velocities (up to half the velocity of light), and is able to efficiently accelerate the neutron star up to millisecond periods. Depending on the Equation of State (EoS) of ultra-dense matter, 0.1–0.2 $M_\odot$ are sufficient to spin up a weakly magnetised neutron star to millisecond periods (Burderi et al. 1999). During this phase, because of the accretion of matter and angular momentum, the neutron star accumulates an extraordinary amount of mechanical rotational energy, up to 1% of its whole rest-mass energy.

4.1.2 *Problems and Confirmation of the Recycling Scenario*

The recycling scenario described above (see e.g. Bhattacharya and van den Heuvel 1991) establishes therefore a clear evolutive link between LMXBs and radio MSPs, with the former being the progenitors of the latter. However, till the end of nineties, there was no observational evidence confirming this evolutive scenario, since there was no evidence that LMXBs could host fast rotating neutron stars. In fact, despite thoroughly searched, no LMXB was found to show coherent pulsations, therefore unveiling its spin frequency. The fact that the large majority of LMXBs does not show coherent pulsations is still a problem. Several explanations have been invoked to interpret this fact, but none of them is fully satisfactory (see also Patruno and Watts 2012, and references therein, for further discussion of this issue). One possibility is that the magnetic axis is aligned with the rotation axis (e.g. Ruderman 1991), but this is excluded by the fact that MSPs, the descendants, show pulsations and therefore the magnetic and rotational axes are not aligned in these systems. Another possibility is that the magnetic field is not strong enough to channel the accreting matter to the neutron star magnetic poles or that optically thick matter around the neutron star may smear the coherent pulsations (e.g. Brainerd and Lamb 1987). However, the large majority of LMXBs are transient systems, showing large variation in luminosity, and going through soft (optically thick) X-ray spectra at high luminosity and hard (optically thin) X-ray spectra at low luminosity. During these stages the accretion rate decreases, the accreting matter becoming optically thin, allowing in principle the detection of X-ray pulsations at millisecond periods (e.g. Göğüş et al. 2007). Other two possibilities are that the neutron star magnetic field is buried by long phases of accretion (e.g. Romani 1990; Cumming et al. 2001) or that the coherent pulsations are very weak, beyond the sensitivity of current X-ray observatories.

Another problem of the recycling scenario was the lack of the observational link between LMXBs and MSPs, i.e. the lack of a system behaving like a LMXB during X-ray active phases and like a radio MSP during X-ray quiescence, when presumably the accretion rate goes down and the radio pulsar mechanism can switch on. However, lack of evidence does not mean evidence of lack, and both these problems were recently solved. In particular, in 1998 coherent pulsations were discovered for the first time in a transient LMXB (SAX J1808.4−3658, Wijnands and van der Klis 1998), and in 2013 the long-sought-for missing link between LMXBs and MSPs was finally found (IGR J18245−2452, a.k.a. M28I, Papitto et al. 2013a). In the next section we describe these discoveries and the related ones, and give the basic observational characteristics of these new classes of systems (see Table 4.1 for a summary of the main properties of these systems).

4.2 Millisecond Pulsars in LMXBs and Their Properties

4.2.1 The Discovery of a New Class of Fast Spinning Neutron Star

The situation dramatically changed in 1996, when the NASA observatory Rossi X-ray Timing Explorer (RXTE) was launched. RXTE was the first X-ray observatory coupling a large effective area (the Proportional Counter Array, PCA, had a total collecting area of $\sim$6500 cm^2) and good time resolution (up to 1 μs), hence suitable for the search of fast time variability. In 1996 quasi-coherent pulsations were detected in RXTE observations of the LMXB 4U 1728−34 at a frequency of $\sim$363 Hz, with amplitudes (rms) of 2.5–10% during six of the eight type-I bursts present in the observation (Strohmayer et al. 1996). The pulsations during these bursts showed frequency drifts of 1.5 Hz during the first few seconds but became effectively coherent during the burst decay. The 363 Hz pulsations were interpreted as rotationally induced modulations of inhomogeneous burst emission, and were considered the first compelling evidence for a millisecond spin period in a LMXB.

The direct evidence for the presence of a fast-spinning neutron star in a LMXB arrived 2 years later, in 1998, when observations performed with RXTE led to the discovery of the first millisecond pulsar in a LMXB, SAX J1808.4−3658. This transient LMXB, first observed by the Wide Field Camera (WFC) on board the X-ray satellite BeppoSAX, shows coherent pulsations with a period of 2.5 ms and an orbital period of 2.01 h (Wijnands and van der Klis 1998; Chakrabarty and Morgan 1998). For almost 4 years, SAX J1808.4−3658 was considered as a rare object in which some peculiarity of the system allowed for the detection of the neutron star spin. However, in the last 20 years, other 19 accreting millisecond pulsars have been discovered, the two most recent ones discovered in 2017 (Sanna et al. 2017a; Strohmayer and Keek 2017). All of them show coherent pulsations with periods in the range 1.7–6.0 ms (up to 60 ms if we also include the enigmatic

Table 4.1 Accreting X-ray pulsars in low mass X-ray binaries

Source	ν_s/P (Hz)/(ms)	$P_{\rm orb}$ (h)	f_x ($M_\odot$)	$M_{c,min}$ ($M_\odot$)	Companion type	Ref.
Accreting millisecond pulsars						
XSS J12270−4859	593 (1.7)	6.91	3.9×10^{-3}	0.27	MS	Roy et al. (2015) and de Martino et al. (2014)
PSR J1023+0038	592 (1.7)	4.75	1.1×10^{-3}	0.20	MS	Archibald et al. (2009) and Coti Zelati et al. (2014)
Aql X-1	550 (1.8)	18.95	1.4×10^{-2}	0.56	MS	Casella et al. (2008) and Mata Sánchez et al. (2017)
Swift J1749.4−2807	518 (1.9)	8.82	5.5×10^{-2}	0.59	MS	Altamirano et al. (2011) and D'Avanzo et al. (2011)
SAX J1748.9−2021	442 (2.3)	8.77	4.8×10^{-4}	0.1	MS	Altamirano et al. (2008) and Cadelano et al. (2017)
IGR J17498−2921	401 (2.5)	3.84	2.0×10^{-3}	0.17	MS	Papitto et al. (2011b)
XTE J1814−338	314 (3.2)	4.27	2.0×10^{-3}	0.17	MS	Markwardt and Swank (2003) and Wang et al. (2017)
IGR J18245−2452	254 (3.9)	11.03	2.3×10^{-3}	0.17	MS	Papitto et al. (2013a)
IGR J17511−3057	245 (4.1)	3.47	1.1×10^{-3}	0.13	MS	Papitto et al. (2010)
IGR J00291+5934	599 (1.7)	2.46	2.8×10^{-5}	0.039	BD	Galloway et al. (2005)
SAX J1808.4−3658	401 (2.5)	2.01	3.8×10^{-5}	0.043	BD	Wijnands and van der Klis (1998) and Wang et al. (2013)
HETE J1900.1−2455	377 (2.7)	1.39	2.0×10^{-6}	0.016	BD	Kaaret et al. (2006) and Elebert et al. (2008)
XTE J1751−305	435 (2.3)	0.71	1.3×10^{-6}	0.014	He WD	Markwardt et al. (2002) and D'Avanzo et al. (2009)
MAXI J0911−655	340 (2.9)	0.74	6.2×10^{-6}	0.024	He WD?	Sanna et al. (2017a)
NGC6440 X−2	206 (4.8)	0.95	1.6×10^{-7}	0.0067	He WD	Altamirano et al. (2010)
Swift J1756.9−2508	182 (5.5)	0.91	1.6×10^{-7}	0.007	He WD	Krimm et al. (2007)
IGR J16597−3704	105 (9.5)	0.77	1.2×10^{-7}	0.006	He WD	Sanna et al. (2018)
XTE J0929−314	185 (5.4)	0.73	2.9×10^{-7}	0.0083	C/O WD	Galloway et al. (2002) and Giles et al. (2005)
XTE J1807−294	190 (5.3)	0.67	1.5×10^{-7}	0.0066	C/O WD	Campana et al. (2003) and D'Avanzo et al. (2009)
IGR J17062−6143	164 (6.1)	> 0.28	–	–	–	Strohmayer and Keek (2017)

ν_s is the spin frequency, P_b the orbital period, f_x is the X-ray mass function, $M_{c,min}$ is the minimum companion mass for an assumed NS mass of 1.4 $M_\odot$. The companion types are: *WD* White Dwarf, *BD* Brown Dwarf, *MS* Main Sequence, *He Core* Helium Star

Adapted and updated from Patruno and Watts (2012)

LMXB IGR J17480−2446 recently discovered in the Globular Cluster Terzan 5; Papitto et al. 2011a), and all of them are found in compact systems, with orbital periods in the range 40 min to ∼10 h (with the exception is Aql X-1, one of the so-called intermittent millisecond pulsars, which has an orbital period of 19 h). Hence, very low mass donors, $\leq 0.2\,M_{\odot}$, are usually preferred. Another common feature of these systems is that all of them are transients, spending most of the time in a quiescent X-ray state; on occasions they show X-ray outbursts with moderate peak luminosities in the range 10^{36}–10^{37} erg s^{-1}. It was clear that we were facing a new class of astronomical objects, the so-called Accreting Millisecond X-ray Pulsars (hereafter AMSPs) that could constitute the bridge between the accretion-powered (LMXBs) and the rotation-powered (MSPs) neutron star sources.

4.2.2 Peculiar Behaviours and Intermittent Pulsations

Most (if not all) of the AMSPs are transient, as the vast majority of LMXBs in general. They spend most of time in quiescence with very low X-ray luminosity ($\lesssim 10^{31}$–10^{33} erg s^{-1}) and sometimes they show X-ray outbursts (reaching luminosities of $\sim 10^{36}$–10^{37} erg s^{-1}) usually lasting from few days to ≤3 months. The shortest outburst recurrence time is 1 month for the globular cluster source NGC 6440 X-2, with an outburst duration of less than 4–5 days, whereas the longest outburst, from HETE J1900.1−2455, has lasted for ∼10 years (up to late 2015 when the source returned to quiescence, Degenaar et al. 2017). However, most of these systems have shown just one X-ray outburst during the last 20 years. The most regular among recurrent AMSPs, and therefore the best studied of these sources, is the first discovered AMSP, SAX J1808.4−3658, which has shown an X-ray outburst every 1.6–3.5 years, the latest one occurred in 2015 (Patruno et al. 2017; Sanna et al. 2017b). The outburst light curve is characterised by a fast rise (on a couple of days timescale), a slow exponential decay (with a timescale of ∼10 days) followed by a fast decay (with a timescale of ∼2 days). After the end of the main outburst, usually a flaring activity, called *reflares*, is observed, with a quasi-oscillatory behaviour and a variation in luminosity of up to three orders of magnitude on timescales ∼1–2 days. Moreover a strong ∼1 Hz oscillation is observed to modulate the reflares. A similar behaviour was also observed in the AMSP NGC 6440 X-2 (see e.g. Patruno and D'Angelo 2013). The reflaring behaviour has no clear explanation. Patruno et al. (2016) proposed a possible explanation in terms of either a strong propeller with a large amount of matter being expelled from the system or a trapped (dead) disc truncated at the co-rotation radius.

Another peculiar behaviour is the intermittency of the pulsations, important because it could bridge the gap between non-pulsating LMXBs and AMSPs. In 2005, the seventh discovered AMSP, HETE J1900.1−2455, went into X-ray outburst and showed X-ray pulsations at 377 Hz, with an orbital period of 1.39 h (Kaaret et al. 2006). Contrary to the usual behaviour of AMSPs, this outburst lasted for about 10 years. After the first 20 days of the outburst, the pulsations became intermittent for about 2.5 years. After that the pulsed fraction weakened with stringent upper limits ($\leq 0.07\%$, Patruno 2012). The most puzzling behaviour in this sense, was observed in the LMXB Aql X-1, which showed coherent X-ray pulsations, discovered in 1998 RXTE archival data, that appeared in only one $\sim$150 s data segment out of a total exposure time of 1.5 Ms from more than 10 years of observations (Casella et al. 2008). The third intermittent pulsar is SAX J1748.9$-$2021, where pulsations were detected sporadically in several data segments and in three out of four outbursts observed by the source (Patruno et al. 2009a, see also Sanna et al. 2016 reporting on the 2015 outburst of the source). Interestingly, these AMSPs may have a long term average mass accretion rate higher with respect to the other AMSPs. To explain this behaviour, it has been proposed that a screening of the neutron star magnetic field by the accreting matter weakens its strength by orders of magnitude on timescale of few hundred days, so that it is less effective in truncating the accretion disc and channel matter to the magnetic poles (Patruno 2012). However, it is not clear if this hypothesis can explain all the phenomenology and more observations and theoretical efforts are needed to reach a satisfactory explanation.

A detailed review of most of the phenomenology of AMSPs can be found in Patruno and Watts (2012). In the following we will give an overview of the most debated issues on these systems, with particular attention to aspect regarding their evolution and their connection to rotation-powered MSPs.

4.2.3 Accretion Torques and Short-Term Spin Variations

Accretion torque theories can be tested studying the spin variations of AMSPs during accretion states. These studies can provide valuable information on the mass accretion rate and magnetic field of the neutron star in these systems, as well as their spin evolution. An open question is whether these accreting pulsars are spinning up during an outburst and spinning down in quiescence as predicted by the recycling scenario. Coherent timing has been performed on several sources of the sample, with controversial results. Although some AMSPs show pulse phase delays distributed along a second order polynomial, indicating an almost constant spin frequency derivative, other sources show strong timing noise which can hamper any clear measurement of the spin derivative. In fact, the phase delays behaviour as a function of time in these sources is sometimes quite complex and difficult to interpret, since phase shifts, most probably related to variations of the X-ray flux, are sometimes present.

The first AMSP for which a spin derivative has been measured is the fastest spinning ($\sim$599 Hz, in a 2.46 h orbit) among these sources, IGR J00291+5934. It is now generally accepted that this source shows spin up at a rate of $\sim(5\text{–}8) \times 10^{-13}\,\mathrm{Hz\,s^{-1}}$ (Falanga et al. 2005; Patruno 2010). Burderi et al. (2006) have attempted to fit the phase delays vs. time with physical models taking into account the observed decrease of the X-ray flux as a function of time during the X-ray outburst, with the aim to get a reliable estimate of the mass accretion rate onto the compact object. In the hypothesis that the spin-up of the source is caused by the accretion of matter and angular momentum from a Keplerian accretion disc, the mass accretion rate, $\dot{M}$, onto the neutron star can be calculated by the simple relation: $2\pi I\dot{\nu} = \dot{M}(GM_{NS}R)^{1/2}$, where I is the moment of inertia of the neutron star, $\dot{\nu}$ the spin frequency derivative, G the gravitational constant, M_{NS} the neutron star mass, R the accretion radius, and $(GM_{NS}R)^{1/2}$ the Keplerian specific angular momentum at the accretion radius. Because the X-ray flux, which is assumed to be a good tracer of the mass accretion rate, is observed to decrease along the outburst, this has to be included in the relation above in order to obtain the correct value of the mass accretion rate at the beginning of the outburst as well as its temporal evolution. Note that the accretion radius also depends on the mass accretion rate, $R \propto \dot{M}^{-\alpha}$, where α is usually assumed to be $2/7$ (e.g. Ghosh and Lamb 1978), and therefore varies with time. Fitting the phase delays in this way, the spin frequency derivative at the beginning of the outburst results to be $\dot{\nu} \sim 1.2(2) \times 10^{-12}\,\mathrm{Hz\,s^{-1}}$, and the lower limit to the mass accretion rate at the beginning of the outburst, corresponding to $\alpha = 0$, is $\dot{M}_{-10} = 5.9\dot{\nu}_{-13}I_{45}m^{-2/3} = 70 \pm 10$, where $\dot{M}_{-10}$ is the mass accretion rate in units of $10^{-10}\,M_{\odot}\,\mathrm{year}^{-1}$, $\dot{\nu}_{-13}$ is the spin frequency derivative in units of $10^{-13}\,\mathrm{Hz\,s^{-1}}$, I_{45} the moment of inertia of the neutron star in units of $10^{45}\,\mathrm{g\,cm^2}$, and m is the neutron star mass in units of $M_{\odot}$. This would correspond to a bolometric luminosity of $\sim 7 \times 10^{37}\,\mathrm{erg\,s^{-1}}$, that is about an order of magnitude higher than the X-ray luminosity inferred from the observed X-ray flux, assuming a distance of 5 kpc. Once we will have a direct, independent, estimate of the distance to the source, we will have the possibility to test the $\dot{M}$ vs. X-ray luminosity relation, torque theories and/or the physical parameters of the neutron star.

Other AMSPs show clear parabolic trend of the pulse phase delays as a function of time during X-ray outburst, some of them showing spin-up (e.g. XTE J1807−294, $\dot{\nu} = 2.5(7) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$, Riggio et al. 2008; XTE J1751−305, $\dot{\nu} = 3.7(1.0) \times 10^{-13}\,\mathrm{Hz\,s^{-1}}$, Papitto et al. 2008; IGR J17511−3057, $\dot{\nu} = 1.6(2) \times 10^{-13}\,\mathrm{Hz\,s^{-1}}$, Riggio et al. 2011a) while others showing spin-down (e.g. XTE J0929−314, $\dot{\nu} = -9.2(4) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$, Galloway et al. 2002; XTE J1814−338, $\dot{\nu} = -6.7(7) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$, Papitto et al. 2007; IGR J17498−2921, $\dot{\nu} = -6.3(1.9) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$, Papitto et al. 2011b). Those sources showing spin-down suggest the possibility of an interaction of the neutron star magnetic field with the accretion disc outside the co-rotation radius (the radius in the disc where the Keplerian frequency equals the neutron star spin frequency). In fact the magnetic field lines can be threaded into the accretion disc and dragged by the high conductivity plasma so that an extra torque due to magnetic stresses has to be expected (see e.g. Wang 1987). In this case, an estimate of the magnetic field strength can be derived from the measured spin-down rate (see e.g. Di Salvo et al. 2007). However, there is not a general consensus on the interpretation of these phase residuals. Another possibility is that these are due to a timing noise caused by a pulse phase offset that varies in correlation with X-ray flux, such that noise in flux translates into timing noise (Patruno et al. 2009b). In this case, much stringent limits result on the spin derivatives in these sources (see Patruno and Watts 2012, and references therein). Although for some sources clear correlations are observed between abrupt jumps in the pulse phases and sharp variations in the X-ray flux, it is not clear yet how much of the phase variations can be ascribed to an accretion-rate-dependent hot spot location.

Certainly, the most debated case is SAX J1808.4−3658 whose phase variations are strongly dominated by timing noise. The pulse phase delays show a very puzzling behaviour, since a rather fast phase shift, by approximately 0.2 in phase, is present at day 14 from the beginning of the 2002 outburst (Burderi et al. 2006) (see Fig. 4.1, left panel). Interestingly, day 14 corresponds to a steepening of the exponential decay with time of the X-ray flux. However, analysing separately the phase delays of the fundamental and second harmonic of the pulse profile, Burderi et al. (2006) noted that the phase delays of the harmonic did not show any evidence of phase jumps (see Fig. 4.1, right panel). This is not an effect of the worse statistics of the phase delays derived from the harmonic, which of course show larger error bars.

This means that the phase jump in the fundamental is not related to an intrinsic spin variation (which would have affected the whole pulse profile), but is instead caused by a change of the shape of the pulse profile (perhaps related to the mechanism causing the increase of the steepness of the exponential decay of the X-ray flux). On the other hand, from the fitting of the phase delays of the second harmonic, under the hypothesis that these are a better trace of the spin of the neutron star, Burderi et al. (2006) find that the source shows a spin-up at the beginning of the outburst with $\dot{\nu}_0 = 4.4(8) \times 10^{-13}\,\mathrm{Hz\,s^{-1}}$, corresponding to a mass accretion rate of $\dot{M} \sim 1.8 \times 10^{-9}\,M_\odot$ year^{-1}, and a constant spin-down, with $\dot{\nu}_{sd} = 7.6(1.5) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$, dominating the phase delays at the end of the outburst. In this case, the mass accretion rate inferred from timing is only a factor of 2 larger than the observed X-ray luminosity at the beginning of the outburst, that is $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$. The spin-down observed at the end of the outburst can be interpreted as due to a threading of the accretion disc by the neutron star magnetic field outside the co-rotation radius. Of course, in agreement with the expectation, the threading effect appears to be more relevant at the end of the outburst, when the mass accretion rate significantly decreases. In this case the magnetic moment, μ, of SAX J1808.43658 can be evaluated from the measured value of the spin-down, using the relation (see Rappaport et al. 2004):

$$2\pi I \dot{\nu}_{sd} \equiv \frac{\mu^2}{9r_{\mathrm{cor}}^3} \tag{4.3}$$

where r_{cor} is the co-rotation radius. The magnetic field found in this way is $B = (3.5 \pm 0.5) \times 10^8$ G, perfectly in agreement with other, independent, constraints (e.g. Burderi et al. 2006).

The fact that the second harmonic shows more regular phase residuals with respect to the fundamental has also been observed in other AMSPs (e.g. Riggio et al. 2008, 2011a; Papitto et al. 2012) and may indicate that the second harmonic is a good tracer of the neutron star spin frequency. A simple model proposed by Riggio et al. (2011b) (see also Papitto et al. 2012) may explain a similar behavior

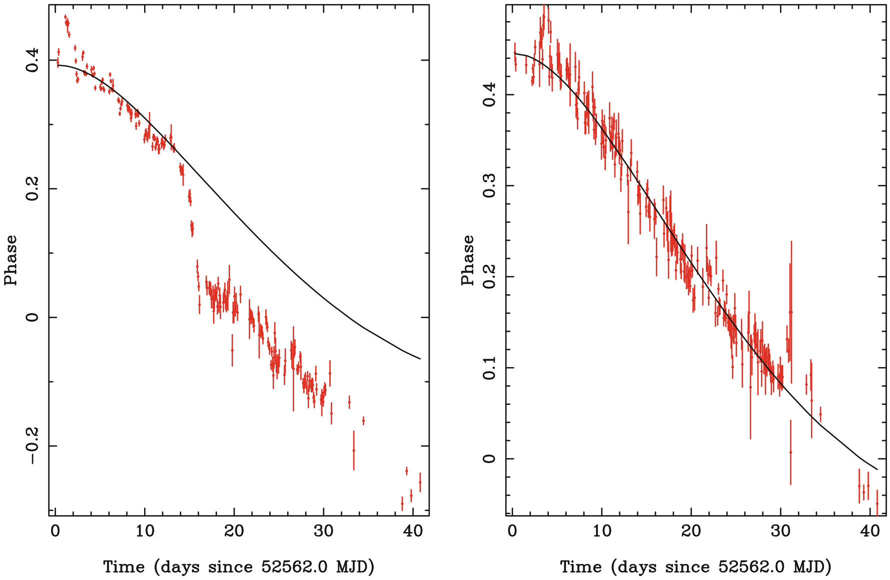

Fig. 4.1 **Left:** Phase vs. time for the fundamental of the pulse frequency of SAX J1808.4−3658. **Right:** Phase vs. time for the first harmonic of the pulse frequency of SAX J1808.4−3658. On top of the data, the best-fit function (including both the spin-up due to accretion and the spin-down at the end of the outburst) is plotted as a solid line (from Burderi et al. 2006)

in terms of modest variations of the relative intensity received by the two polar caps on to the neutron star surface, in the hypothesis that the two spots emit a signal of similar amplitude and with a similar harmonic content. The sum of the two signals (the total profile) will be the result of a destructive interference for what concerns the fundamental frequency, since it is the sum of two signals with a phase difference of $\sim\pi$. A constructive interference develops instead for the second harmonic of the total profile, since it is the sum of two signals with the same phase. The destructive interference regarding the fundamental frequency leads to large swings of the phase of the fundamental of the total profile due to modest variations of the relative intensity of the signals emitted by the two caps. In this case swings up to 0.5 phase cycles can be shown by the phase computed over the fundamental frequency of the observed profile, without correspondingly large variations of the phase of the second harmonic. Interestingly, IGR J00291+5934, showing a much more regular behaviour of the fundamental, shows a nearly sinusoidal pulse profile, with very little harmonic content (e.g. Galloway et al. 2005; Burderi et al. 2007).

4.2.4 Long-Term Spin Evolution

For AMSPs for which more than one outburst has been observed, it is possible to derive their long term spin evolution comparing the averaged spin frequency measured in each outburst. To date only six AMSPs have been monitored with high time resolution instruments in different outbursts: SAX J1808.4−3658, IGR J00291+5934, XTE J1751−305, Swift J1756.9−2508, NGC6440 X-2 and SAX J1748.9−2021 (although, with relatively low S/N and short outburst duration in the latter two sources). The best constrained is SAXJ1808.4−3658, for which secular spin evolution have now been measured over a 13 year baseline and shows a constant long-term spin-down at a rate of $\sim -1 \times 10^{-15}\,\mathrm{Hz\,s^{-1}}$ (Hartman et al. 2008, 2009; Patruno et al. 2012; Sanna et al. 2017b). Because of the stability of the spin-down rate over the years, the most likely explanation appears to be loss of angular momentum via magnetic-dipole radiation, which is expected for a rapidly rotating neutron star with a magnetic field. The measured spin-down is consistent with a polar magnetic field of $(1.5\text{–}2.5) \times 10^{8}$ G. This is in agreement with the estimate above.

A spin down has also been measured for IGR J00291+5934 between the 2004 and 2008 outburst, at a rate of $-4.1(1.2) \times 10^{-15}\,\mathrm{Hz\,s^{-1}}$ (Patruno 2010; Papitto et al. 2011c; Hartman et al. 2011), larger than that observed in SAX J1808.43658, as expected given that IGR J00291+5934 spins at a higher frequency. If interpreted in terms of magneto-dipole emission, the measured spin down translates into an estimate of the neutron star magnetic field of $(1.5\text{–}2) \times 10^{8}$ G. For the period between the 2008 and 2015 outbursts only an upper limit to the frequency evolution could be derived, $|\dot{\nu}| \leq 6 \times 10^{-15}\,\mathrm{Hz\,s^{-1}}$ (3σ c.l., Sanna et al. 2017c), compatible with the previous estimate. Comparing the spin frequencies from 2002, 2005, 2007 and 2009 outbursts of XTE J1751−305, Riggio et al. (2011c) report a spin down at a rate of $\sim(1.2) \times 10^{-15}\,\mathrm{Hz\,s^{-1}}$ and an inferred magnetic field of $\sim 4 \times 10^{8}$ G. Whereas for Swift J1756.9−2508 only an upper limit ($|\dot{\nu}_{sd}| \leq 2 \times 10^{-15}\,\mathrm{Hz\,s^{-1}}$), corresponding to a magnetic field $\leq 10^{9}$ G, has been reported (Patruno et al. 2010).

The fact that the spin-down during quiescent periods is probably due to magnetic-dipole radiation rises the interesting possibility that AMSPs may switch on as a radio pulsar during quiescence and ablate their donor. This is the so-called *hidden black widow* scenario proposed by Di Salvo et al. (2008) (see also Stella et al. 1994; Campana et al. 1998) to explain the long-term orbital evolution (see next section).

4.2.5 Orbital Evolution

The study of the orbital evolution in these systems is important to constrain the evolutionary path leading to the formation of radio MSPs. These studies, however, require a large timespan of data in order to constraint the orbital period derivative.

Hence, the main difficulty is given by the fact that most of the AMSPs rarely turn into X-ray outburst. For this reason, the best constraints on the orbital evolution in these systems come again from SAX J1808.4−3658, which has shown seven X-ray outburst to date, allowing to follow its orbital period over 17 years.

In the case of SAX J1808.4−3658 it is possible to see a clear parabolic trend of the time of passage to the ascending node versus time over the last 17 years (Di Salvo et al. 2008; Hartman et al. 2008; Burderi et al. 2009; Patruno et al. 2016; Sanna et al. 2017b). Interpreting this parabolic term as the orbital period derivative, gives orbital expansion at a quite high rate of $\dot{P}_{orb} = (3.4\text{–}3.9) \times 10^{-12}\,\mathrm{s\,s^{-1}}$ (see also Sanna et al. 2016 who report a marginally significant, strong orbital expansion in the AMSP SAX J1748.9−2021). The observed orbital expansion implies a mass-radius index for the secondary $n < 1/3$ (see Di Salvo et al. 2008). In the reasonable hypothesis that the secondary star is a fully convective star out of thermal equilibrium and responds adiabatically to the mass transfer, a mass-radius index of $n = -1/3$ can be assumed for the secondary. However, this derivative is a factor ∼70 higher that the orbital derivative expected for conservative mass transfer, given the low averaged mass accretion rate onto the neutron star; since SAX J1808.4−3658 accretes for about 30 d every 2–4 year, the averaged X-ray luminosity from the source results to be $L_{obs} \sim 4 \times 10^{34}\,\mathrm{erg\,s^{-1}}$.

A non-conservative mass transfer can explain the large orbital period derivative if we assume a mass transfer rate of $\dot{M} \sim 10^{-9}\,M_{\odot}\,\mathrm{year}^{-1}$, and that this matter is expelled from the system with the specific angular momentum at the inner Lagrangian point (see Di Salvo et al. 2008; Burderi et al. 2009). In this case, the non-conservative mass transfer may be a consequence of the so-called *radio-ejection* model extensively discussed by Burderi et al. (2001). The basic idea is that a fraction of the transferred matter in the disc could be swept out by radiative pressure of the pulsar. In this case, the fast spinning neutron star may ablate the companion during quiescent periods (the so-called hidden black widow scenario proposed by Di Salvo et al. 2008). Alternatively, the large orbital period derivative observed in SAX J1808.4−3658 can be interpreted as the effect of short-term angular momentum exchange between the mass donor and the orbit (Hartman et al. 2009; Patruno et al. 2012), resulting from variations in the spin of the companion star (holding the star out of synchronous rotation) caused by intense magnetic activity driven by the pulsar irradiation. This mechanism has been invoked by Applegate and Shaham (1994) (hereafter A&S) to explain oscillating orbital residuals observed in some radio MSPs (see e.g. Arzoumanian et al. 1994). In this case, the energy flow in the companion needed to power the orbital period change mechanism can be supplied by tidal dissipation. However, the A&S mechanism envisages alternating epochs of orbital period increase and decrease, which is not yet observed from SAX J1808.4−3658. It also predicts that the system will evolve to longer orbital periods by mass and angular momentum loss on a timescale of 10^8 year (for a 2-h orbital period and a companion mass of 0.1–0.2 $M_{\odot}$), and thus requires a strong orbital period derivative, similar to that inferred from the quadratic trend observed in SAX J1808.4−3658. Therefore, also in the framework of the A&S mechanism, most of the orbital period variation observed in SAX J1808.4−3658 is probably caused by loss of matter and angular momentum, i.e. by a non-conservative mass transfer (see Sanna et al. 2017b for further discussions). The next outbursts from this source will tell us whether the orbital period increase will turn into a decrease or, instead, the orbital expansion will continue, and this will be crucial in order to discriminate between the two possibilities sketched above.

Another puzzling result comes from IGR J0029+5934, which has orbital parameters very similar to those of SAX J1808.4−3658, and is considered its *orbital twin*. IGR J0029+5934 has shown only four outbursts since its discovery, but tight upper limits could be derived on its orbital period derivative, $|\dot{P}_{orb}| < 5 \times 10^{-13}\,\mathrm{s\,s^{-1}}$ (90% confidence level Patruno 2017, see also Sanna et al. 2017c). This implies a much slower orbital evolution, on a timescale longer than $\sim$0.5 Gyr, as compared to the fast orbital evolution of its twin, $\sim$70 Myr. The orbital evolution observed in IGR J0029+5934 is compatible with the expected timescale of mass transfer driven by angular momentum loss via gravitational radiation, with no need of A&S mechanism or non-conservative mass transfer. In this case, it would be interesting to constrain the sign of the orbital period derivative in order to get information on the mass-radius index of the donor star and to infer whether it is in thermal equilibrium (implying orbital contraction) or not (implying orbital expansion).

4.2.6 Searches at Other Wavelengths

AMSPs are transient systems with inferred variations in the mass accretion rate onto the central source by a factor of $\sim 10^5$ between outbursts and quiescence. Since the magnetospheric radius expands as the mass accretion rate decreases, it is easy to see that, while during an X-ray outburst the magnetospheric radius is expected to be very close to the neutron star surface, during X-ray quiescence the magnetospheric radius may expand beyond the light-cylinder radius (where an object co-rotating with the neutron star attains the speed of light). In this case, it is expected that any residual accretion is inhibited by the radiation pressure and, consequently, it is plausible to expect that the neutron star turns-on as a radio MSP until a new outburst episode pushes the magnetospheric radius back again, quenching radio emission and initiating a new accretion phase. The compelling possibility that these systems could swiftly switch from accretion-powered to rotation-powered magneto-dipole emitters during quiescence gives the opportunity to study a phase that could shed new light on the not yet cleared up radio pulsar emission mechanism. However, such a behaviour has been observed only recently, in the so-called transitional MSPs (see next sections), and in particular in the unique source IGR J18245−2452 (Papitto et al. 2013a), the long-sought-for "missing link" between LMXBs and radio MSPs; a binary system containing a neutron star alternating accretion-powered phases, in which it behaves like an AMSP, to rotation-powered phases, in which it behaves like a radio MSP. However, despite the huge observational effort made to catch, in a transient LMXB, the transition between the accretion-powered regime and the rotation-powered regime during quiescence, no pulsed radio emission has been found in other AMSPs. The most embarrassing problem is certainly the lack of pulsed radio emission from these systems during quiescence: many transient LMXBs and AMSPs have been thoroughly searched in radio during quiescence with disappointing negative results (Burgay et al. 2003; Iacolina et al. 2009, 2010; Patruno et al. 2017).

Burderi et al. (2001) (see also Burderi et al. 2002) have proposed a model, that naturally explains this non-detection, assuming that the radio pulsar mechanism switches on when a temporary significant reduction of the mass-transfer rate occurs. In some cases, even if the original mass transfer rate is restored, the accretion of matter onto the neutron star can be inhibited by the radiation pressure from the radio pulsar, which may be capable of ejecting out of the system most of the matter overflowing from the companion-star Roche lobe. In particular, Burderi et al. (2001) showed that in “wide systems”, i.e. systems with orbital periods longer than a few hours, and with a sufficiently fast spinning neutron star, the switch-on of the radio pulsar can prevent any further accretion, even if the original mass transfer rate is restored. On the other hand, “compact” systems (orbital periods below a few hours) should show a cyclic behaviour since, once the temporary reduction of the accretion rate ends, the radiation pressure of the pulsar is unable to keep the matter outside the light cylinder radius and accretion resumes.

One of the strongest predictions of this model is the presence, during the radio-ejection phase, of a strong wind of matter emanating from the system: the mass released by the companion star swept away by the radiation pressure of the pulsar. This matter could cause strong free-free absorption in the radio band, hampering the detection of pulsed signals. A possible solution is then to observe at high radio frequencies (above 5–6 GHz, see Campana et al. 1998; Di Salvo and Burderi 2003), thus reducing the cross-section of free-free absorption which depends on ν^{-2}. Note that the pulsed radio flux also decreases with increasing frequency, although it is easy to see that this decrease is less steep with respect to the decrease of the effects caused by free-free absorption (see e.g. Burderi and King 1994). This may explain why some AMSPs indeed have radio counterparts (see Patruno and Watts 2012 for a review), although not pulsating. Interestingly, Iacolina et al. (2010) report a peak at 4σ significance for XTE J1751−305, obtained folding a radio observation of this source performed at Parkes radio telescope. This peak has a 40% probability of not being randomly generated over the 40,755 trial foldings of the dataset corresponding to one of the two observations performed at 8.5 GHz. This result is not confirmed in the other observation (at the same frequency) and thus deserves additional investigation in the future. Alternatively, pulsating radio emission should be searched in systems with long orbital periods, in which the matter transferred by the companion star is spread over a wider orbit.

Strong (indirect) evidences that a rotating magneto-dipole powers the quiescent emission of AMSPs, comes from observations of the quiescent emission from their identified optical counterpart. In the case of SAX J1808.4−3658, measures in the optical band show an unexpectedly large optical luminosity (Homer et al. 2001), inconsistent with both intrinsic emission from the companion star and X-ray reprocessing. The most probable explanation for the over-luminous optical counterpart of SAX J1808.4−3658 in quiescence, proposed by Burderi et al. (2003) and Campana et al. (2004), is that the magnetic dipole rotator is active during quiescence and its bolometric luminosity, given by the Larmor's formula (Eq. (4.1)), powers the reprocessed optical emission. Indeed, the optical luminosity and colours predicted by this model are perfectly in agreement with the observed values.

Similar results have been obtained for other AMSPs for which optical observations in quiescence have been performed. For XTE J0929−314 and XTE J1814−338, optical photometry in quiescence showed that the donor was irradiated by a source emitting in excess of the X-ray quiescent luminosity of these sources, requiring an energy source compatible with the spin-down luminosity of a MSP (D'Avanzo et al. 2009). IGR J00291+5934 showed evidences for a strongly irradiated companion in quiescence too (D'Avanzo et al. 2007).

The precise spin and orbital ephemerides of AMSPs are of fundamental importance to allow deep searches of their counterparts in the gamma-ray band, which has the advantage of not suffering the free-free absorption as in the radio band, but the disadvantage of the paucity of photons, which requires folding over years in order to reach the statistics needed for detecting a pulsed signal. Indeed, AMSPs, in analogy with MSPs (such as the so-called Black Widows and Red-Backs, detected in radio and most of them also in the gamma band; see Roberts 2013 as a review) are expected to show coherent pulsations in the gamma band during X-ray quiescence. The detection of a possible gamma-ray counterpart of the AMSP SAX J1808.4−3658 from 6 years of data from the Fermi/Large Area Telescope has been recently reported (de Oña Wilhelmi et al. 2016). The authors also searched for modulations of the flux at the known spin frequency or orbital period of the pulsar, but, taking into account all the trials, the modulation was not significant, preventing a firm identification via time variability. We expect that this result may be improved increasing the time span of the gamma-ray data.

4.3 The Missing Link

As we described in the previous sections a clear path has been delineated bringing an old, slowly spinning neutron star to become a millisecond radio pulsar. The last link of the chain was supposed to be disclosed with the discovery of the (transient) accreting millisecond X-ray pulsar SAX J1808.4−3658 (Wijnands and van der Klis 1998). But this source, as well as all the other of this class, do not show a radio pulsar soul during their quiescence (even if indirect hints for a turn on of the relativistic pulsar wind have been gathered, Burderi et al. 2003; Campana et al. 2004).

A new way was paved by radio surveys. The Faint Images of the Radio Sky at Twenty-cm (FIRST) radio survey carried out at the Very Large Array (VLA) covered ∼10,000 square degrees discovering nearly one million of radio sources. Matching radio sources with optical surveys Bond et al. (2002) reported the discovery of a new magnetic cataclysmic variable with radio emission: FIRST J102347.6+003841 (hereafter J1023). Optical spectroscopic studies revealed the presence of an accretion disc in 2001 through the presence of double-horned emission lines (Szkody et al. 2003), which led Thorstensen and Armstrong (2005) to suggest that J1023 could be a neutron star low-mass X-ray binary. A bright millisecond radio pulsar (1.69 ms) was discovered in 2007 coincident with J1023 (Archibald et al. 2009). No signs of an accretion disc are discernible any more but the pulsed radio signal was eclipsed sporadically along the 4.8 h orbit. This was the first system testifying for the alternating presence of an accretion disc and of a millisecond radio pulsar, thus providing the first indirect evidence that the two souls can live within the same object.

Nature did even better. IGR J18245−2452 (J18245 hereafter) was discovered as a new X-ray transient in the globular cluster M28. XMM-Newton pointed observations revealed a pulsed signal at 3.93 ms making of J18245 an accretion X-ray pulsar, modulated at 11 h orbital period (Papitto et al. 2013a). Coincidentally, a radio pulsar was detected during a radio survey of M28 with the same spin period and binary orbital period (PSR 18245−2452I). J18245 closed definitely the chain: it is the first pulsar ever detected in X-rays and at radio wavelengths. Twenty days after the end of the outburst J18245 was detected again as a radio pulsar, closing the loop and demonstrating that the transition between the rotation-powered and the accretion-powered regime can occur on short timescales.

Incidentally, in mid 2013 the radio monitoring of J1023 failed to detect the radio pulsar any more. Simultaneously the optical, X-ray and gamma-ray flux increased by a factor of ∼70 and ∼5, respectively, even if the source did not enter in a proper outburst state (Patruno et al. 2014; Stappers et al. 2014). During this active state J1023 displayed a very peculiar behaviour with three different states: a high state during which X-ray pulsations are detected, a low state (a factor of ∼7 dimmer) during which no pulsations were detected (and the upper limit on the pulsed fraction is lower than what observed during the high state) and a flaring state (with no pulsations too), outshining both states during which the source wildly varies. Transitions occur on a ∼10 s timescale in X-rays (Archibald et al. 2015; Bogdanov et al. 2015). More details will be provided in the next section (see also Fig. 4.2). Another source distinctly showed this behaviour was XSS J12270−4859 (Papitto et al. 2015) (J12270 in the following), so that this puzzling X-ray light curve has become the archetypal way to identify a “transitional” X-ray pulsar.

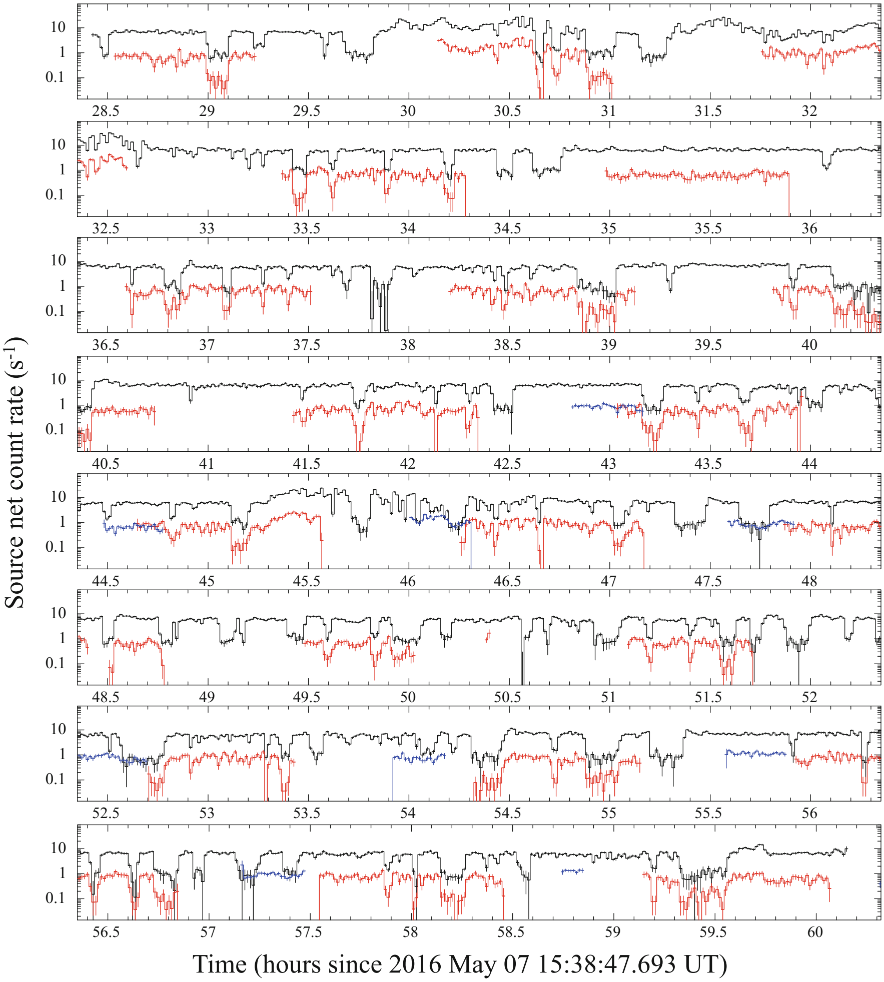

Fig. 4.2 Background-subtracted and exposure-corrected light curves of J1023 obtained with the XMM-Newton EPIC cameras (0.3–10 keV; black data), NuSTAR FPMA + FPMB (3–79 keV; red data) and Swift UVOT (UVM2 filter; blue data) during the time interval covered by XMM-Newton. For plotting purpose, light curves are shown with a binning time of 50 s and the vertical axis is plotted in logarithmic scale (from Coti Zelati et al. 2018)

4.4 Madamina, il catalogo è questo ("Don Giovanni", Mozart)

There are four transitional pulsars and a few candidates. At the moment of writing (October 2017) J1023 is in an active state. J18245 and J12270 are in quiescence, shining as radio pulsars. We summarise their main characteristics in Table 4.2.

Table 4.2 Parameters of transitional millisecond pulsars

Source	Spin period (ms)	Orbital period (h)	Distance (kpc)	Companion mass ($M_\odot$)	DM (pc cm^{-3})	Fermi detection	X-ray pulsations	Radio pulsations
J1023	1.69	4.75	1.37	~0.24	14.3	Y	Y	Y
J12270	1.69	6.91	1.4	~0.25	43.4	Y	Y	Y
J18245	3.93	11.03	5.5 (M28)	~0.2	119	N	Y	Y
J154439	–	~ 5.3	–	–	–	Y	N	N

4.4.1 PSR J1023+0038

J1023 was discovered as a peculiar magnetic cataclysmic variable with radio emission (Bond et al. 2002). Optical studies revealed signs for the presence of an accretion disc through double horned emission lines in 2001 (Szkody et al. 2003; Wang et al. 2009). Thorstensen and Armstrong (2005) performed photometric and spectroscopic optical observations campaign. The spectrum showed mid-G star features and the disappearance of the accretion disc signatures. Photometry showed a smooth orbital modulation at 4.75 h, with colour changes consistent with irradiation (but with no emission lines). Radial velocity studies and modelling of the light curves led them to show that the primary should be more massive than the Chandrasekhar mass, thus pointing to a LMXB, rather than a cataclysmic variable. Homer et al. (2006) used XMM-Newton data, lack of optical circular polarisation, and optical spectroscopic data to confirm this picture.

This changed with the discovery of a radio pulsar coincident with J1023. Archibald et al. (2009) discovered a bright, fast spinning (1.69 ms) MSP during a low-frequency pulsar survey carried out with Green Bank Telescope in 2007. The pulsar is eclipsed during a large fraction of the orbital period (at orbital phases 0.10–0.35). Due to its proximity and radio brightness it was possible to derive a very precise distance of 1.37 ± 0.04 kpc based on its radio parallax (Deller et al. 2012). XMM-Newton observations then revealed a $\sim 9 \times 10^{31}$ erg s^{-1} (0.5–10 keV) source showing pulsed emission at the radio period. The root-mean-squared pulsed fraction in the 0.25–2.5 keV energy range is 11 ± 2%, whereas a 3 σ upper limit of 20% is obtained at higher energies (Archibald et al. 2010; Bogdanov et al. 2011). The neutron star's parameters were determined thanks to the radio pulsar signal, with a spin period of 1.69 ms and a dipolar magnetic field of 9.7×10^7 G (Archibald et al. 2009; Deller et al. 2012).

Surprisingly, J1023 started not being detected in the radio band around June 2013 (Patruno et al. 2014; Stappers et al. 2014). Contemporaneously, the weak γ-ray flux detected by Fermi increased by a factor of ~5 (Stappers et al. 2014; Takata et al. 2014; Torres et al. 2017). This new state persisted in time and J1023 is still in this active state now (October 2017) with no signs of change. Together with the disappearance of the radio signal, J1023 brightened at all the other wavelengths. In the X-rays (0.5–10 keV) it brightened by a factor of ~30, with some flaring activity

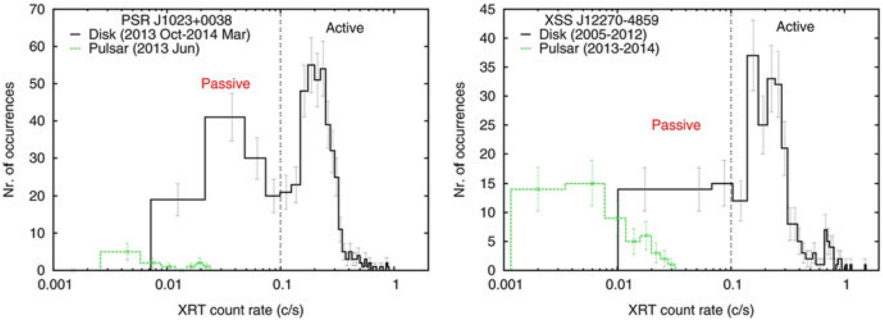

Fig. 4.3 Count rate distribution in the 0.3–10 keV XRT light curves of J1023 (left) and J12270 (right). The disc state (solid black histogram) and pulsar state (dashed green histogram) are shown separately on the same scale. The horizontal dotted line at 0.1 c s^{-1} for both sources marks the boundary between disc-active and disc-passive states (labeled in black and red, respectively, from Linares 2014)

reaching 10^{34} erg s^{-1} (Patruno et al. 2014; Takata et al. 2014; Coti Zelati et al. 2014; Bogdanov et al. 2015). In the optical, J1023 brightened too by ∼1 mag and showed again the presence of several broad, double-horned emission lines typical of an accretion disc (Halpern et al. 2013; Coti Zelati et al. 2014).

At variance with any other LMXBs, J1023 shows a highly variable active state. A simple histogram of the observed count rates shows a bimodal distribution (Linares 2014) (see Fig. 4.3). A closer look (thanks to XMM-Newton observations) revealed the existence of three distinct states (Bogdanov et al. 2015; Archibald et al. 2015). These can be characterised as:

- a high state with a 0.3–80 keV luminosity $L_X \sim 7 \times 10^{33}$ erg s^{-1} (Tendulkar et al. 2014) occurring for ∼80% of the time and during which X-ray pulsations at the neutron star spin period are detected with a r.m.s. pulsed fraction of $8.1 \pm 0.2\%$ (0.3–10 keV) (Archibald et al. 2015);
- a low state with a 0.3–80 keV luminosity $L_X \sim 10^{33}$ erg s^{-1} occurring for ∼20% of the time and during which pulsations are not detected with a 95% r.m.s. upper limit $\lesssim 2.4\%$ (0.3–10 keV), much smaller than the detection during the high state;
- a flaring state during which sporadic bright flares occur reaching luminosities as high as of $\sim 10^{35}$ erg s^{-1}, with no pulsation too.

The transition between the high and the low states is very rapid, on a ∼10 s timescale and looks symmetric (ingress time equals to the egress time). It is not clear if similar variability has also been detected in the optical band, superimposed to the orbital modulation (Shahbaz et al. 2015; Jaodand et al. 2016). A phase-connected timing solution shows that the neutron star is spinning down at a rate ∼30% faster than the spin down due to rotational energy losses (Jaodand et al. 2016).

The 0.1–300 GeV flux of increased by a factor of ∼5 after the transition to the active state with a steep power law photon index of 2.5–3 (Stappers et al. 2014; Takata et al. 2014; Deller et al. 2015). Above 300 GeV VERITAS put instead an 95% upper limit of $7 \times 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ on the flux (Aliu et al. 2016).

Radio monitoring observations during the active state revealed a rapidly variable, flat spectrum persistent source. This emission is likely suggesting synchrotron emission as the origin. If this is in form of a jet or more generally of a propeller outflow is unknown (Deller et al. 2015). In addition, based on existing correlation in neutron star LMXBs between the radio luminosity and the X-ray luminosity, J1023 is brighter in radio, possibly suggesting a less efficient X-ray emission (Deller et al. 2015). Baglio et al. (2016) measured a linear polarisation of $0.90 \pm 0.17\%$ in the R band. In addition, the phase-resolved R-band curve shows a hint for a sinusoidal modulation. Lacking the Spectral Energy Distribution a red/nIR excess (characteristic of jet emission), the polarised emission likely comes from Thomson scattering with electrons in the disc.

Simultaneous X-ray (Chandra) and radio (VLA) monitoring showed a strong anti-correlated variability pattern, with radio emission strongly rising during X-ray low states (Bogdanov et al. 2018). A more articulated observing campaign involving XMM-Newton, NuSTAR, and Swift showed that X-rays al soft and hard (up to 80 keV) are strongly corrected with no lag, whereas X-rays and UV are not correlated (Coti Zelati et al. 2018).

Surprisingly, Ambrosino et al. (2017) discovered optical pulsations in J1023 during the active X-ray state. The pulsed fraction is at a level of ∼1%. Optical pulsation is present only in the high mode as X-ray pulsations (A. Papitto, private communication). This optical pulsed emission is puzzling. Ambrosino et al. (2017) convincingly showed that this emission cannot be explained by the cyclotron mechanism and cautiously favour a rotation-powered regime mechanism.

4.4.2 IGR J18245−2452

IGR J18245−2452 (J18245 in the following) was discovered by INTEGRAL/ISGRI during observations of the Galactic centre region (Eckert et al. 2013). J18245 lies in the globular cluster M28 at a distance of ∼5.5 kpc (Heinke et al. 2013; Romano et al. 2013; Homan and Pooley 2013). At this distance the peak outburst luminosity is $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$ (0.5–100 keV, e.g. De Falco et al. 2017). This luminosity led J18245 to be classified as a classical X-ray transient (i.e. not faint). A thermonuclear (type I) X-ray burst from J18245 was detected by Swift/XRT (Papitto et al. 2013b; Linares 2013). This marked the presence of a neutron star in the system. Further type I bursts were observed during the same outburst by MAXI (Serino et al. 2013) and INTEGRAL (De Falco et al. 2017). During an XMM-Newton observation, Papitto et al. (2013a) discovered a coherent periodicity in the X-ray flux at 3.9 ms. The pulsed signal is also modulated through Doppler shifts at the binary orbital period of 11.0 h, induced by a $\sim 0.2\,M_\odot$ companion star. Papitto et al. (2013a) were also able to associate the X-ray pulsar to a known radio pulsar previously discovered in M28, PSR J1824−2452I (Manchester et al. 2005), with the same spin and orbital periods. This provides the first direct evidence for a switch between an accretion-powered neutron star and a rotation-powered radio pulsar. The reactivation of the radio pulsar was very fast, with the detection of a pulsed signal less than 2 weeks after the end of the outburst.

A very peculiar state was observed when the source luminosity reached a mean level of a few 10^{36} erg s^{-1}. Rapid variation by a factor up to ∼100 were observed during two XMM-Newton observations (Ferrigno et al. 2014). In a hardness-intensity diagram two branches can be identified (see Fig. 4.4; Ferrigno et al. 2014). The brighter branch (blue branch) showed a tight correlation between hardness and intensity (as well as pulsed fraction). Below a threshold of ∼30 c s^{-1} in the pn instrument in addition to this branch a new one (magenta branch), appeared with scattered points at higher hardness. J18245 varied by a factor of ∼100 on a timescale as short as a few seconds. A spectral analysis at different spectral hardness shows a clear decrease in the power law spectral index from $\Gamma \sim 1.7$ to $\Gamma \sim 0.9$ and the disappearance of a black body component. The hardest spectrum is better described by partially covering power law model and it is achieved only occasionally at low count rates. A pulsed signal is always detected and the pulsed fraction is tightly correlated with the source count rate. In the magenta branch there is however no correlation of the hardness with the pulsed fraction, which is always at a level of 5–10% (Ferrigno et al. 2014).

M28 has been observed several times, however only thanks to the spatial resolution of the Chandra optics it is possible to gain information on the quiescence of J18245. Chandra observed M28 in 2002 finding J18245 in a quiescent state. The X-ray spectrum is well described by a simple power law model with a hard

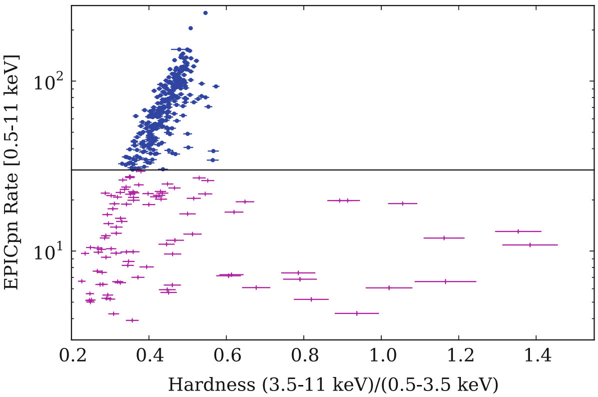

Fig. 4.4 Hardness-intensity diagram built by using two XMM-Newton observations with time bin of 200 s. The black solid line separates the different intensity states: the points represented in magenta and blue have a count rate lower and higher than 30 c s^{-1}, respectively (from Ferrigno et al. 2014)

photon index $\Gamma \sim 1.2$. The 0.5–10 keV unabsorbed luminosity is $\sim 2 \times 10^{32}$ erg s^{-1} (Linares et al. 2014). No room for a soft component is left with an upper limit on the 0.1–10 keV luminosity of $\lesssim 7 \times 10^{31}$ erg s^{-1}. In a way similar to J1023 (but before J1023), also J18245 shows two different low-luminosity active states. They are readily apparent in a long Chandra observation taken in 2008 (Linares et al. 2014). The high and low state 0.5–10 keV luminosities are $\sim 4 \times 10^{33}$ erg s^{-1} and $\sim 6 \times 10^{32}$ erg s^{-1}, respectively, with a factor of $\sim$7 luminosity change. The spectra in the two states are fully compatible with a power law with photon index $\Gamma \sim 1.5$. Given the lower Chandra count rate, mode switching has been measure to occur on a timescale of $\lesssim 200$ s.

The optical counterpart has been identified thanks to HST images (Pallanca et al. 2013). The companion star has been detected during both quiescence and outburst, showing a two magnitude increase and the presence of the Hα line, indicating that accretion is taking place.

PSR J18242452I is known as a radio pulsar in M28 (detected during the quiescent period), but its observations were only sporadic and with large eclipses, variable from orbit to another as often happens in redbacks. In addition, the acceleration induced by the motion in the globular cluster prevents us from a firm measurement of the magnetic field.

4.4.3 XSS J12270−4859

XSS J12270−4859 (J12270 in the following) was discovered by the Rossi X-ray Timing Explorer during the high latitude slew survey (Sazonov and Revnivtsev 2004). Based on the presence of optical emission lines J12270 was initially classified as a cataclysmic variable hosting a magnetic white dwarf (Masetti et al. 2006; Butters et al. 2008), as for J1023. Unusual dipping and flaring behaviour led several authors to suggest a different classification involving a neutron star in a LMXB (Pretorius 2009; Saitou et al. 2009; de Martino et al. 2010, 2013; Hill et al. 2011; Papitto et al. 2015). de Martino et al. (2010) (see also Hill et al. 2011) were the first to associate J12270 to a relatively bright gamma-ray source detected by Fermi-LAT and emitting up to 10 GeV (3FGL J1227.9−4854). The source was puzzling and has been observed during this active state by XMM-Newton. An erratic behaviour typical of TMSP has been observed (de Martino et al. 2010). Despite flaring and dips, J12270 was stable at least over a 7 year period (de Martino et al. 2013). Dips correspond to the low state of J1023. A detailed analysis of the dips in J12270 disclosed three different types of dips: soft dips, dips with no spectral changes with respect to the active state and hard dips following flares. The pn spectrum can be modelled with a simple power law resulting in spectral indexes of: 1.64 ± 0.01 (active state); 1.65 ± 0.03 (flares); 1.71 ± 0.04 (dips), and 0.74 ± 0.08 (post-flare dips; de Martino et al. 2013). The 0.2–100 keV mean luminosity is 10^{34} erg s^{-1} at a distance of 1.4 kpc. The ratio between the active and dip 0.2–10 keV luminosity is ~5, with the active 0.2–10 keV luminosity being 4×10^{33} erg s^{-1} (de Martino et al. 2013).

The XMM-Newton Optical Monitor (OM) was operated in fast timing mode (U and $UVM2$ filters) allowing for a strict comparison with X-ray data. The mean U magnitude was 16.6. Orbital modulation is readily apparent in the OM data. On top of this dips and flares are also present in the OM data, with a drop in the UV count rate by a factor of ~1.4 (de Martino et al. 2013). A lag analysis was also possible, showing no lag among soft (0.3–2 keV) and hard (2–10 keV) X-ray flux. The cross-correlation between U-band and X-rays show no lag, but indications that flares last longer in the optical-UV bands. A cross-correlation analysis on selected dips shows that UV and X-ray dips occur almost simultaneously, but the shape of UV dips is shallower, with a smoother decay and rise (de Martino et al. 2013). The optical spectrum shows prominent Hα, Hβ, He I, He II, and Bowen-blend N III/C III lines, as well as signs of irradiation (de Martino et al. 2014).

As J1023 during its active state also J12270 has been detected by Fermi in the 0.1–300 GeV, with a 0.1–10 GeV flux of 4×10^{-11} erg cm^{-2} s^{-1} and a steep power law spectrum with $\Gamma \sim 2.2$ and a cut-off energy of 8 GeV (Johnson et al. 2015; de Martino et al. 2010). Faint non-thermal radio emission was also detected with a flat spectral index (Masetti et al. 2006; Hill et al. 2011).

J12270 remained stable at all wavelengths for about a decade up to 2012 November/December, when a decline in flux at all bands was reported (Bassa et al. 2014; Bogdanov et al. 2014). This is in all respects similar to the transition of J1023 in the opposite sense: J12770 changed from an active state to a quiescent state, whereas the opposite transition was observed in J1023 in June 2013. J12270 decreased its optical brightness by 2 magnitudes, with all the optical emission lines disappearing. The X-ray spectrum hardened considerably with the spectrum described by power law with a photon index of $\Gamma = 1.1$ and a 0.3–10 keV unabsorbed luminosity of $\sim 2 \times 10^{32}$ erg s^{-1}, resulting in a factor of ~20 decrease with respect to the high state and ~4 with respect to the low state (de Martino et al. 2015; Bogdanov et al. 2014). At GeV energies the 0.1–100 GeV flux decreased by a factor of ~2 and the spectrum hardened to a power law with photon index 1.7 with a cut-off at 3 GeV (Johnson et al. 2015).

Radio observations revealed the presence of a millisecond radio pulsar at the position of J12270. The neutron star is spinning at 1.69 ms and has a magnetic field of 1.4×10^{8} G (for a rotational energy of 9×10^{34} erg s^{-1}; Roy et al. 2015). The radio signal is absorbed for a large fraction of the orbit. After this discovery pulsations were searched at other frequencies and in older data. Pulsed emission was observed at GeV energies with a single peak emission nearly aligned with the radio main peak (Johnson et al. 2015). The pulsed signal was not detected in the X-ray band with a 3 σ upper limit on the rms pulsed fraction of ~7% (full band) or ~10% (0.5–2.5 keV; Papitto et al. 2015). Papitto et al. (2015) reanalysed XMM-Newton data during the high state and, knowing the pulse period, successfully detected a coherent pulsation. Pulsations were detected at an rms amplitude of ~8%, with a second harmonic stronger than the fundamental frequency. The amplitude is similar in the soft and hard X-ray bands. Polarimetric optical observation during the quiescent radio pulsar state, failed to detect any signal with a $3\,\sigma$ upper limit of 1.4% in the R band (Baglio et al. 2016).

4.4.4 1RXS J154439.4−112820

After the recognition of a peculiar variability pattern during the active state of J1023 and J12270, searches for new members of the transitional MSPs started, searching for rapid variability in the X-ray light curve of unidentified sources or cataclysmic variables and association with Fermi sources. With these characteristics Bogdanov and Halpern (2015) identified the forth member of the TMSP class in 1RXS J154439.4−112820 (J154439 in the following). J154439 is the only X-ray source within the 95% error circle of the Fermi source 3FL J1544.6−1125 (Stephen et al. 2010). J154439 has also been detected during the XMM Slew survey and by Swift/XRT, with flux variations by a factor of ∼3. Masetti et al. (2013) provided evidence for the presence of prominent emission lines (H and He) in the $R \sim 18.4$ optical counterpart, suggesting its identification as a cataclysmic variable.

During an XMM-Newton observation, J154439 showed characteristic rapid variations on a timescale of ∼10 s, passing randomly from ∼2 to $\sim 0.2\,\mathrm{c\,s^{-1}}$ and back. The overall spectrum is well fit with an absorbed power law model with $\Gamma = 1.7$ ($N_H = 1.4 \times 10^{21}\,\mathrm{cm^{-2}}$, consistent with the Galactic value). Spectral variations are only marginally evident with indexes of 1.67 ± 0.04 and 1.97 ± 0.28 (90% confidence level) for the high and low states, respectively (Bogdanov and Halpern 2015). Even if pn data were taken in timing mode, no X-ray periodicity was reported. A NuSTAR observation confirmed the spectral parameters over the 0.3–79 keV energy band, leading to a luminosity of $10^{33}\,\mathrm{erg\,s^{-1}}$ at a scale distance of 1 kpc (Bogdanov 2016). Fast photometric data taken at the MDM Observatory showed fast variability also in the optical counterpart. MDM data and XMM-Newton/OM data revealed hints for an orbital modulation at a period of ∼5.2–5.4 h.

4.5 Once Upon a Time There Were a Magnetic Neutron Star Interacting with an Accretion Disc

The transition from and to the radio pulsar regime observed in the three well studied TMPS J1023, J18245, and J12270 with a good degree of certainty involves the presence of an accretion disc. In addition to an enhanced emission at all wavelengths, double horned emission lines were observed. This testifies that the switch on and off of the radio pulsar mechanism in binary systems can occur, at least, on timescales of tens of days and it is not a single occurrence in the neutron star lifetime.

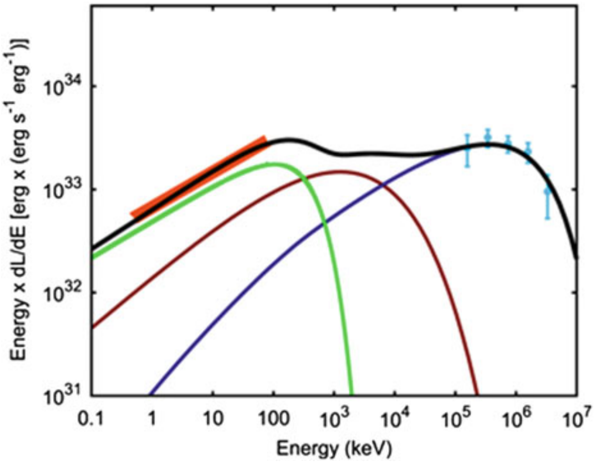

Fig. 4.5 Average spectral energy distribution (SED) observed from PSR J1023+0038 in X-rays (orange strip, from Tendulkar et al. 2014), and gamma-rays (cyan points, from Takata et al. 2014), evaluated for a distance of 1.37 kpc. The total SED evaluated with Papitto and Torres (2015) modelling is plotted as a black solid line. Synchrotron, Synchrotron-Self-Compton, and accretion flow (i.e. the sum of disc and neutron star emission) components are plotted as red, blue and green lines, respectively

The inference of the root cause of the sub-luminous disc state is more complicated. This sub-luminous state is dominated ($\sim$80% of the time) by the high mode during which X-ray pulsations are observed (e.g. in J1023). For this high mode Papitto and Torres (2015) (see also Bednarek 2015) showed that a scenario based on the propeller can explain the observed features at all wavelengths. The spectral energy distribution is characterised a broad emission from X-rays to gamma-rays (see Fig. 4.5). Papitto and Torres (2015) interpreted the gamma-ray part as due to the self-synchrotron Compton emission that originates at the turbulent boundary between the neutron star magnetosphere propelling the disc inflow at super-Keplerian speed. The X-ray emission is instead due to the sum of the synchrotron emission that originated from the same magnetospheric region and the luminosity emitted by the accretion flow, which however must be inefficient ($\lesssim$ 20% of the conversion of gravitational energy) not to exceed the observed one.

Different suggestions have been put forward to explain the transitions among high and low mode (and flaring) and, more importantly, why only the three known TMSPs show this puzzling behaviour (and stability). The flux drops that bring the sources to the low mode are extremely peculiar and are very different from the dips currently observed in LMXBs, since there are no associated spectral changes and/or reduction of the soft X-ray flux, excluding absorption from intervening matter. Apparently, there is also no evidence for an X-ray luminosity dependence on the duration and frequency of flares and low flux mode intervals or any correlation between the separation between (and duration of) dips or flares (Bogdanov et al. 2015).

The fate of matter falling onto a magnetic neutron star is determined by the position of three different radii. Two are fixed and depends on the neutron star spin period: the corotation radius $r_{\rm cor} = (G\,M_{NS}\,P^2/(4\,\pi^2))^{1/3}$ (where magnetic field lines reach the Keplerian speed) and the light cylinder radius $r_{\rm lc} = c\,P/(2\,\pi)$ (with c the light velocity, where the magnetic field lines open, being unable to corotate with the neutron star). The truncation of the accretion disc by the magnetosphere occurs at the magnetospheric radius $r_{\rm m} = \xi\,(\mu^2/(2\,G\,M\,\dot{M}^2))^{1/7}$, with $\xi \sim 0.5$ (Campana et al. 2018) accounting for the disc geometry, $\mu = B\,R_{NS}^3$ the dipole magnetic moment, and $\dot{M}$ the mass accretion rate at the magnetospheric boundary. If the magnetospheric radius lies within the corotation radius, accretion proceeds unimpeded, however if $r_{\rm m} > r_{\rm cor}$ the incoming matter experiments a centrifugal force larger than gravity when it gets attached to the fields lines at the magnetospheric radius and (ideally) gets propelled out. If the mass accretion rate decreases further, $r_{\rm m}$ expands further, reaching at some point the light cylinder radius. At this point the magnetic field becomes radiative and matter is expelled further out by radiation pressure and relativistic particle wind (Campana et al. 1998; Burderi et al. 2001). A radio pulsar can in principle start working again. The observed luminosity in the sub-luminous state of J1023 and J12270 is relatively low and at the corresponding mass accretion rate (assuming that all the accreting material arrives at the neutron star surface) implies a magnetospheric radius well outside the corotation radius (Archibald et al. 2015; Bogdanov et al. 2015; Campana et al. 2016), so that the sources should be in the propeller regime. This poses a problem and suggests intriguing new insights for accretion physics at low luminosities.

The best and well studied example of propeller accretion is probably the accreting white dwarf AE Aquarii. In this system only $\sim$0.3% of the incoming material is able to reach the star surface. In AE Aqr most of the soft X-ray luminosity is produced in the inflow before ejection or accretion onto the surface (Oruru and Meintjes 2012). Correlation and lag analysis can shed light on the emission mechanisms in TMPS. J1023 has been well characterised. Hard (NuSTAR) and soft (XMM-Newton) X-ray emission appear well correlated (Coti Zelati et al. 2018). X-rays (XMM-Newton) instead do not correlate with UV (Swift/UVOT, Coti Zelati et al. 2018) nor with optical (B) emission (XMM-Newton/OM, Bogdanov et al. 2015), unless during the flaring state. This suggests that at least in J1023, as for AE Aqr, UV-optical emission comes from the accretion disc and the companion star.

Jaodand et al. (2016) were able to measure the overall period evolution of J1023. They found that J1023 is spinning down at a rate that is $\sim$30% larger than the pure dipole spin-down rate. This is consistent with the modelling of Parfrey et al. (2017) of AMSP magnetospheres in which the spin-down during propeller has the same functional form of the pulsar spin down and depends on how the disc inside the light cylinder opens some of the closed field lines, leading to an enhancement of the power extracted by the pulsar wind and the spin-down torque applied to the pulsar.

One class of scenarios involves a trapped disc. A propeller may not be able to eject matter so that the inflaming matter stays confined in the innermost part of the flow, trapping the magnetospheric radius close to the corotation radius (D'Angelo and Spruit 2010, 2012). Pure trapped disc models will not work being the oscillation timescale much shorter than what observed (Bogdanov et al. 2015). The switching between low and high mode might be the result of transitions between a non-accreting pure propeller mode and an accreting trapped-disc mode (Archibald et al. 2015; Bogdanov et al. 2015).

Alternatively, Campana et al. (2016) (see also Linares et al. 2014) proposed that high mode is connected to the propeller regime, whereas the low mode to the expulsion of the infalling matter by the neutron star pressure, with the neutron star in the radio pulsar state. During the high mode in the propeller regime, some matter leaks through the centrifugal barrier and accretes onto the neutron star, as shown in magnetohydrodynamical simulations (Romanova et al. 2005), and generates the observed X-ray pulsations. Detailed spectral modelling is consistent with a radiatively inefficient accretion disc close to the corotation radius during the high mode and receding beyond the light cylinder during the low mode. Contemporarily a shock emission sets in. Pulsed emission at a lower amplitude ($\sim$2–3%) and in the soft band only is predicted to occur. This scenario is in agreement with the broadband modelling by Papitto and Torres (2015) and by the observed optical polarisation coming from the disc (Baglio et al. 2016) and flat radio spectrum (Deller et al. 2015). The strong anti-correlation among X-ray and radio emission (Bogdanov et al. 2018) fits perfectly within this scenario: during the low state matter is expelled from the system by the relativistic pulsar wind generating in the shock strong radio emission. Parfrey and Tchekhovskoy (2018) showed through general-relativistic MHD simulations that this scenario is plausible.

A completely different scenario (Jaodand et al. 2016) is motivated by the observation of mode switching in radio pulsars, in which the pulse profile switches between two stable profiles. PSR B0943+10 showed that the mode switching in radio is accompanied by simultaneous switches in the X-ray band (profile and intensity; Mereghetti et al. 2013; Hermsen et al. 2013). Mode switching has never been observed in any X-ray pulsar so for the moment this might remain an intriguing suggestion.

Optical pulsations in the active X-ray state are puzzling. Ambrosino et al. (2017) showed that cyclotron emission can be ruled out and a rotation-powered mechanism might work. A pure (engulfed) radio pulsar however encounters problems in explaining the full phenomenology of J1023 (Campana et al. 2016). As noted in Bogdanov et al. (2018) J1023 and the other transitional ms pulsars are the only systems for which the neutron star rotational energy is comparable to the accretion energy. It might be that the neutron star always looses rotational energy, independently of the fate of the accreting matter. Accretion of matter is able to quench pulsed radio emission but pulsed optical emission might be generated. In this case we would expect pulsed optical emission to be present independently on the X-ray mode.

4.6 Open Questions

Among all the open questions that we described above, the most puzzling problem still regards the connection between LMXBs and AMSPs, or MSPs in general. It is still a mystery the reason why LMXBs usually do not show X-ray pulsations, not even at low mass accretion rates when presumably the magnetospheric radius is outside the neutron star surface and inside the co-rotation radius, thus allowing matter to be channelled by the magnetic field. Does it have to do with the magnetic field, that can be buried inside the neutron star surface by prolonged accretion phases? Another mystery is why AMSPs, although fast spinning and with a misaligned magnetic field do not show pulsed radio or gamma emission (as instead do other not accreting MSPs, including transitional MSPs) in quiescence, when accretion onto the neutron star decreases by orders of magnitude presumably pushing the magnetospheric radius outside the light cylinder radius. Does it have to do with the presence of matter around the system that is swept away by the radiation pressure of the pulsar? Is this enough to justify also non detections in the gamma-ray band? In other words, it would be important to understand why a system like J18245 (a.k.a. M28I), swinging between the rotation-powered and the accretion-powered phase in such short timescales is so rare. Is it because of its relatively large ($\sim$11 h) orbital period so that the matter outflowing the system is spread in a relatively wide orbit?

On the TMSP side, we have a number of open questions that will likely be answered in the next following years. Why do some sources (J1023 and XSS12270) showed a long (years) accretion-dominated state whereas J18245 showed a proper X-ray outburst? Why do the accretion-dominated state of these systems so stable (e.g. in J1023)? What is the root cause of the mode switching observed during the accretion-dominated state? Are X-ray pulsations detectable at a lower level (and/or in a softer energy band) also in the low mode of the active X-ray state? These are the basic questions that make these systems particularly attractive.

Recently optical pulsations detected in J1023 added a number of additional questions. What is the mechanism responsible for optical pulsation? Is the accretion-dominated state really powered by accretion? Can a rotation-powered mechanism remain active (i.e. not inhibited) during an accretion state?

Answering these questions will give important information on the still elusive radio pulsar and accretion emission mechanisms and on the evolutive path producing the different types of MSPs known today.

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