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On low mass X-ray binaries and millisecond pulsar

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Abstract. The detection, in 1998, of the first Accreting Millisecond Pulsar, started an exiciting season of continuing discoveries in the fashinating field of compact binary systems harbouring a neutron star. Indeed, in these last three lustres, thanks to the extraordinary performances of astronomical detectors, on ground as well as on board of satellites, mainly in the radio, optical, x–ray, and gamma–ray bands, astrophysicists had the opportunity to thoroughly investigate the so–called Recycling Scenario: the evolutionary path leading to the formation of a Millisecond Radio Pulsar. The most intriguing phase is certainly the spin–up stage during which, 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. These millisecond spinning neutron stars are truly 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 just beyond their Schwartzscild Radius, and electrodynamical 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 Radio and Gamma–ray. 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 one hundred suns. Along these fifteen years, a fruitful collaboration was established, at the Rome Astronomical Observatory, between my group and Franca D'Antona: her profound knowledge of the complex phases of stellar evolution, in particular of low–mass stars in close binary systems, was the key ingredient which boosted our theoretical and experimental studies of different evolutionary stages of these intriguing and fashinating systems. In this paper I will review some of the most recent discoveries on (accreting) millisecond pulsars, highlighting the role played by our proficuous collaboration.

Key words. Stars: neutron – Stars: magnetic fields – Pulsars: general – X-rays: binaries — X-rays: pulsars

1. Introduction

The classycal Recycling Scenario explains Neutron Stars (NS hereafter) spinning at mil-

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lisecond periods as the result of accretion of matter and angular momentum from Roche Lobe overflow of a low–mass companion ($\leq$ 1 $M_{\odot}$) in a semi–detached system (see *e.g.* Bhattacharya & van den Heuvel, 1991, for a review). According to this model, a subclass of NS Low Mass X-ray Binaries (LMXBs, hereafter), are the progenitors of the Millisecond Radio Pulsars (MSPs, hereafter). This model has been quite successful inexplaining and predicting several properties of binary MSPs populationwith low mass, degenerate (Withe Dwarfs), companions like their orbital period distributions and companion masses (see *e.g.* Podsiadlowski, Rappaport & Pfahl, 2002 for detailed numerical orbital evolutions of short orbital period systems in which the mass-transfer is driven by magnetic braking and/or gravitational radiation (hereafter MB and GR, respectively), and the classical work of Webbink, Rappaport and Savonije, 1983, for semi–analytical evolution for long period systems driven by stellar evolution of the companion off the main sequence branch; see also Verbunt 1993 for a comprehensive review). However, three observational facts were difficult to reconcyle with the predictions of the Recycling Scenario: *i)* the lack of LMXBs showing millisecond X–ray pulsations, *ii)* the fact that some (up to 20%) of MSPs are isolated, *iii)* the lack of NS spinning below $\sim$ 1.4 ms (the shortest spin period detected up to date: PSRJ1748–244ad, Hessels *et al.* 2006), since the shortest spin periods attainable for NSs are well below one millisecond for most of the proposed equation of state of the ultradense matter (see *e.g.* Lavagetto *et al.* 2004, 2005 and references therein).

In 1998, the discovery of coherent millisecond X–ray pulsations at 2.5 ms in SAX J1808.4-3658, a transient LMXB observed, during an X-ray outburst, by the *Rossi* X-ray Timing Explorer satellite (RXTE, hereafter) solved *i)* by demonstrating that indeed some LMXBs host a weakly magnetized, millisecond spinning NS (Wijnands & van der Klis 1998): the long sought progenitors of MSPs were eventually found (the difficulty in detecting them was the weak pulsed fracion, few percent, ascribed to the weakness of the magnetic field strength, and the short orbital period of the binary, about 2 h for SAX J1808.4-3658, causing a further reduction of the power of the coherent signal because of strong Doppler modulation).

Following this first discovery a total of 14 Accreting Millisecond X–ray Pulsar (AMP, hereafter) were discovered to date, all in compact binaries ($P_{\rm ORB}$ < 1 d), all transient LMXB, few recurrent (see Table 1).

In the following I will quickly reviev all the major progresses made, in recent years in the topics outline above.

2. Accretion in LMXBs: the fifteen golden years of AMPs

A possible solution to *ii)* arrived after the discovery (Fruchter, Stinebring & Taylor 1988) of the original "Black Widow" B1957+20, a radio eclipsing MSP spinning at 1.6 ms in a close ($P_{\rm ORB} \sim 9.2$ h) binary system with a very low mass companion ($M_2 \sim 0.02\ M_{\odot}$). It has been proposed that isolated MSPs have ablated their companions by means of low–freqency electromagnetic radiation, energetic particles and/or Gamma–rays produced by the fast rotating magnetic dipole (see *e.g.* Ruderman, Shaham & Tavani 1989). The huge NS rotational energy, stored during the accretion phase, $E_{\rm ROT}/(Mc^2) = 0.011\ I_{45} P_{-3}^{-2} m^{-1}$ erg, is released according to the Larmor's formula: $L_{\rm SD} = (2/3c^3)\mu^2(2\pi/P^4) = 3.85 \times 10^{35} B_8^2 R_6^6 P_{-3}^{-4}$ erg/s, where M ($m = M/{\rm M}_{\odot}$), R (R_6 in units of 10^6 cm), and I (I_{45} in units of 10^{45} erg cm^2) are the NS mass, radius, and moment of inertia, respectively, P (P_{-3} in units of 10^{-3} s) is the NS spin period, $\mu = BR^3$ is the NS magnetic moment, B (B_8 in units of 10^8 Gauss) is the dipolar magnetic field strength at the NS magnetic equator, ($\mu_{26} = \mu/(10^{26}$ Gauss cm$^3) = 1$ for $B_8 = R_6 = 1$), and c is the speed of light. Thus, in case of no accretion, the dipolar magnetic field strength at the NS equator is $B_8 = 1.01\ R_6^{-3} I_{45}^{1/2} (P_{-3}\dot{P}_{-20})^{1/2}$, where $\dot{P}_{-20} = dP/dt/10^{-20}$.

To solve *iii)* the emission of GR from rapidly spinning NS has been proposed (see *e.g.* Chakrabarty et al. 2003, Melatos & Payne 2005 for models of a non-zero mass quadrupole for an accreting pulsar), although, in most models, the onset of rotational instabilities, that cause the emission of GR, are predicted to occur at spin periods much shorter than the minimum observed (see *e.g.* Burderi & D'Amico, 1997).

Alternatively, to simultaneously explain *ii)* and *iii)*, our group proposed (Burderi et al. 2001) an evolutionary phase, that we dubbed "Radio Ejection" (RE, hereafter), that unavoidably triggers during accretion for systems with $P_{\rm ORB} \geq P_{\rm CRIT} \sim 1.05 \text{ h} \times L_{36}^{51/25} m^{1/10} \mu_{26}^{-24/5} P_{-3}^{48/5} \times \left[1 - 0.462 \left(\frac{m_2}{m+m_2}\right)^{1/3}\right]^{-3/2} (m + m_2)^{-1/2}$, where L_{36} is accretion luminosity in units of 10^{36} erg/s, $m_2 = M_2/{\rm M}_\odot$. Indeed, since $P_{\rm CRIT} \propto P^{10} B^{-5}$, it quickly decreases below 1 h as P decreases towards 1 ms during the LMXB phase, for any $B > 10^8$ Gauss. Which eventually causes the onset of RE for *any* system with $P_{\rm ORB} \geq 1$ h. During this phase, the radiation pressure of the rotating magnetic dipole ($p_{\rm RAD}(R_{\rm RL}) = L_{\rm SD}/(4\pi c R_{RL}^2)$, where $R_{\rm RL}$ is the distance of the Inner Lagrangian Point from the NS centre) is sufficient to halt and expel the matter overflowing the inner Lagrangian point with a pressure $p_{\rm RAM}(R_{\rm RL}) = 0.5\rho v^2 \sim \dot{M}\sqrt{GM/R}/(8\pi R_{\rm RL}^2)$. Similat to ablation, RE is more effective in "evaporating" the companion, since it maximizes the fraction of $L_{\rm SD}$ intercepted by the companion, and minimize the specific binding energy of the matter that has to be ejected, explaining *ii)*. Moreover, the P^{10} dependence of $P_{\rm CRIT}$, acts as a barrier allowing $P \ll 1.4$ ms only for extremely compact systems $P_{\rm ORB} \ll 1$ h. Strong Doppler modulation severely hampers the detection of a coherent signal in these cases, explaining *iii)*.

A spectacular confirmation of our model was the discovery of the eclipsing pulsar PSRJ1740–5340 in the Globular Cluster NGC6397 ($P_3 = 3.65$, $B_8 = 7.7$,$P_{\rm ORB} = 1.35$ d, $m_2 \geq 0.19$, D'Amico et al. 2001) and the subsequent identification of its optical companion (Ferraro et al. 2001) which showed evidence of ellipsoidal modulation and a size (determined by the duration of eclipses) only consistent with a Roche Lobe filling companion. Burderi, D'Antona, & Burgay (2002) argued that PSRJ1740–5340 is in the RE phase. Using the ATON1.2 code (D'Antona, Mazzitelli, & Ritter 1989) we were able to effectively model the binary evolution, considering the heating of the companion because of $L_{\rm SD}$, successfully reproducing the peculiar Hertzsprung–Russel diagram location of the optical companion.

More recently, radio observations of Gamma–ray sources detected by the Fermi satellite allowed to discover many (43 so far) MSPs, with an extreme high fraction of eclipsing sources in compact binaries, 21 up to date. This has opened a unique opportunity to deeply study these systems, given that, in the 20 years from the discovery of the original Black Widow B1957+20 (1990) up to the Fermi era (2009), only 3 eclipsing MSP were discovered (see Roberts 2012 for a review). Eclipsing MSPs in compact systems ($P_{\rm ORB} \lesssim 1$ d) were recently classified in "Black Widows" (14 out of 21, BW, hereafter) and "Redbacks" (7 out of 21, after the Australian cousin of the poisonus American spider, RB, hereafeer), depending on the companion mass ≤ 0.1 M$_\odot$ for BW, and $\gtrsim 0.1$ M$_\odot$. Companion masses are derived from optical observations (Betron et al. 2013), indicating that, over a total of 17 BW and 7 RB, 21 have sizes ≥ 0.8 of their Roche Lobes.

We argue that: a) PSRJ1740–5340 can be considered the first discovered (prototype) RB, b) BW and RB are almost all in RE phase. Otherwise, if the companion underfills its Roche Lobe, and no mass–transfer occurs, it would be difficult to imagine a mechanism to replenish the plasma responsible for the eclipses, as discussed in Breton et al. (2013). Our evolutionary scenario predicts this, since we showed that the onset of RE is the natural outcome for any system with $P_{\rm ORB} \geq 1$ h.

The discovery of AMPs offered the unique opportunity to verify, during the accretion phase, the evolutionary path outlined above. This has been made possible thanks to the compelling opportunity of applying the accurate machinery of timing analysis to millisecond "clocks" moving in close orbits. In particular the astonishing precision of these tecniques allowed to highlight, at least in some cases, the istantaneous effect of the accretion of angular momentum onto the NS, through an accurate measure of the NS spin–up rate. This is a strong verification of several underlying hypothesis usually postulated in the Recycling Scenario.

Given the NS spin–up rate, adopting a reasonable prescription for the torque exerted by the accretion flow (*e.g.* that the matter accretes its specific angular momentum at the point where is captured by the NS magnetic field), it is possible to verify the presence of matter orbiting in a Keplerian accretion disc truncated at the magnetospheric radius $R_{\rm m}$, comparable to the Alfvén radius. This is the radius where the energy density of the NS magnetic dipole is equal to the energy density of the accretion flow, assumed in free fall: $R_{\rm A} = (2GM)^{-1/7}\dot{M}^{-2/7}\mu^{4/7} = 9.90 \times 10^5 m^{-1/7} m_{-8}^{-2/7} (B_8 R_6^3)^{4/7}$ cm, where G is the gravitational constant, $\dot{M}$ ($m_{-8} = \dot{M}/(10^{-8}{\rm M}_\odot/{\rm yr})$) is the accretion rate.

Moreover, since the dynamical effect of accretion is measured directly through the spin–up rate, this independent estimate of $\dot{M}$ can be compared with the X–ray (almost bolometric) luminosity ($L = \eta G M \dot{M}/R$) to infer, given the distance of the source, the efficiency of accretion. The theoretical prediction $\eta \sim 1$ has been experimentally confirmed (see *e.g.* Burderi *et al.* 2007, Papitto *et al.* 2008).

A clear determination of the spin–up rate during the x–ray outburst is *per se* very complex since the expected spin period derivatives are tiny ($\dot{P} \sim 10^{-18}$) (for $m_{-8} \sim 0.1$ corresponding to typical X–ray outburst luminosities of 10^{37} erg/s) acting for just few tens of days (typical outburst duration). This implies variations for the phases of the pulse profile $\Delta\phi/\phi \lesssim 1$. Unfortunately in some cases, phases are affected by strong timing noise with $\Delta\phi_{\rm NOISE}/\phi \lesssim 1$. By expanding the almost sinusoidal pulse profile in a Fourier Series (no more than 4 harmonic components are typically needed, and only the first two are significant in most cases) we performed timing analysis on each component and discovered that, in most cases, the second harmonic component is noise–free and shows a nearly parabolic trend in time, which is expected for a constant spin–up torque (see *e.g.* Burderi *et al.* 2006). We therefore argued that the phases of second harmonic component are a more stable tracer of the NS spin evolution.

To take into account the variations of the accretion rate along the outburst and the threading of the accretion disc by the NS magnetic field, we adopted the torque prescription of Rappaport, Fregeau, & Spruit (2004): $\tau_{\rm NS} = \dot{M}\sqrt{GMR_{\rm CO}} - \mu^2/(9R_{\rm CO}^3)$, where $R_{\rm CO} = 1.5 \times 10^6\ m^{1/3} P_{-3}^{2/3}$ cm is the corotation radius (at which the speed of NS magnetic field lines is equal to the local Keplerian speed in the disc). We were able to perform timing analysis on 7 out of 14 sources in which timing noise was either absent (*e.g.* IGR J00291+5934, Burderi et al. 2007) or strongly suppressed in the second harmonic component (*e.g.* XTE J1807–294, Riggio *et al.* 2008). In 5 cases spin–up consistent with the expectations of the Recycling Scenario was detected, while in 2 cases the detected spin–down suggest the presence of a strong NS magnetic moment (*cf.* the torque formula, above). The presence of the timing noise originally raised doubts on the reliability of the spin period derivatives determined with timing analysis (Hartman et al. 2008). Heterodox phenomenological models in which pulse phases correlate with X–ray luminosities were also proposed (Patruno, Wijnands, & van der Klis 2009). However, at least for the cases in which weak timing noise was present, there is now general consensus that phases are a good tracer of the NS spin (see *e.g.* Patruno 2010).

In the few cases in which the AMPs are recurrent, timing analysis of all the X–ray outbursts allows to compute the secular evolution of orbital parameters and, in particular, of the orbital period. This can be compared with the theoretical predictions derived from the assumption of an orbital evolution driven by angular momentum losses determined by GR and/or MB, as expected in these systems. This has been done for SAX J1808.4-3658, in which we detected orbital expansion at an almost constant rate more than 10 times what is expected by conservative mass transfer from a fully convective and/or degenerate secondary driven by the emission of GR (Di Salvo et al. 2008, Hartman et al. 2008). We performed orbital evolution calculations demonstrating that highly non-conservative (about 99%) mass–transfer could explain the observed orbital expansion. In our model mass transfer proceed at almost constant rate, 99% of this matter is expelled during quiescence and 1% accreted during recurrent outbursts. Severe angular momentum losses, caused by the ejected matter, speed–up orbital evolution increasing mass–transfer rates with respect to those expected by the action of GR (Di Salvo et al. 2008, Burderi et al. 2009). Therefore we argued that SAX J1808.4-3658 is alternating between RE and accretion episodes, which is expected if evolution has driven the system in a phase in which $p_{\mathrm{RAD}}(R_{\mathrm{RL}}) \sim p_{\mathrm{RAM}}(R_{\mathrm{RL}})$. Our evolutionary scenario, outlined above, predicts this behaviour as an equilibrium endpoint of the mass–transfer phase in LMXBs harbouring a magnetized fast spinning NS. Therefore we believe that most of the AMP alternate between accretion and RE phases.

Based on a small increase of the orbital period expansion during the last (2011) outburst, Patruno et al. (2012) concluded that the most plausible explanation for orbital period accelerated expansion was given by a companion spin–orbit coupling (see Applegate & Shaham 1994 for a description of the model). Alternatively we argue that the observed acceleration of the orbital expansion with respect to the constant expansion rate is a necessary consequence of a doubling of the mass-transfer, demonstrated by the doubling of the X–ray flux observed in the 2011 outburst (Burderi *et al.*, *in preparation*).

Given the huge amount of power emitted by the fast spinning magnetic dipole (up to 100 $L_{\odot}$, see above), it is conceivable that during X–ray quiescence, when this luminosity is not overwhelmed by the accretion power, irradiation effects on the face of the companion exposed to the NS dipole radiation, could manifest in a detectable modulation at the orbital period. The attractive idea is to use the companion as a bolometer to chatch the albeit elusive magnetodipole radiation in all the energetic channels in which it is emitted: low frequency ($\nu = 1/P$) electromagnetic waves, γ rays, $e^{+/-}$ pais, etc. From the reasonable assumption that the companion fills its Roche Lobe, the fraction of power intercepted can be accurately determined, which allows to estimate thepower emitted by the rotating magnetic dipole quite accurately, and therefore to infer an independent estimate of the NS magnetic field strength. Burderi *et al.* (2003) applied this idea to interpret the optical luminosity of the companion of SAX J1808.4-3658 during quiescence, which was overluminous for $m_2 \leq 0.18$ (Chakrabarty & Morgan 1998). We found that optical data implied $1 \leq B_8 \leq 5$. This method was subsequently applied with success by several authors (see *e.g.* Campana *et.al.*2004, D'Avanzo *et.al.* 2009).

From what is discussed above, it is clear that a crucial role in the whole Recycling Scenario is played by the magnetic moment of the NS. This is the means by which a fraction of the NS huge mechanical energy (slowly accumulated during the previous, long lasting, accretion phase) is released in the system, altering dramatically its entire evolution. Therefore we finally discuss the estimates of the magnetic field of AMP, through four independent methods, namely: a) X–ray residual luminosity in quiescence (Di Salvo & Burderi 2003), b) optical reprocessing of rotating magneto–dipole radiation, discussed above, c) fitting pulse phase delays with the torque formula discussed above, d) for AMPs showing recurrent outburts, comparing subsequent spin period estimates to infer the secular spin–down induced by L_{SD}. For SAX J1808.4-3658 the following estimates were obtained: method a) $1 \leq B_8 \leq 5$ (Di Salvo & Burderi 2003), method b) $1 \leq B_8 \leq 5$ (Burderi *et. al.* 2003, Campana *et. al.* 2004), method c) $B_8 = 3.5 \pm 0.5$ (Burderi *et. al.* 2006, method d) $B_8 = 0.93 \pm 0.42$ (from Hartman *et. al.* 2011 [1]), method d) $B_8 = 1.62 \pm 0.19$ (from Patruno *et. al.* 2012 [1]). For IGR J00291+5934

[1] The B_8 values reported were derived from the reported values of the secular spin–down through the formula $B_8 = 1.01\ R_6^{-3} I_{45}^{1/2} (P_{-3}\dot{P}_{-20})^{1/2}$, adopting $R_6 = I_{45} = 1$

the following estimates were obtained: method d) $B_8 = 1.40 \pm 0.41$ (Papitto *et. al.* 2011, method d) $B_8 = 1.05 \pm 0.28$ (from Patruno *et. al.* 2010 [1]). For XTE J1751–305 the following estimates were obtained: method d) $B_8 = 4.0 \pm 0.41$ (Riggio *et. al.* 2011. The fact that for SAX J1808.4-3658 the four independent methods furnish values all consistent within each other (at less than 3σ level), suggests the substantial correctness of the overall picture outlined above.

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