Publication Year	2015
Acceptance in OA	2020-03-23T13:11:38Z
Title	X-ray coherent pulsations during a sub-luminous accretion disc state of the transitional millisecond pulsar XSS J12270-4859
Authors	PAPITTO, ALESSANDRO, DE MARTINO, Domitilla, BELLONI, Tomaso Maria Melchiorre, BURGAY, MARTA, PELLIZZONI, ALBERTO PAOLO, POSSENTI, ANDREA, Torres, D. F.
Publisher's version (DOI)	10.1093/mnrasl/slv013
Handle	http://hdl.handle.net/20.500.12386/23459
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY
Volume	449

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **449,** L26–L30 (2015) doi:10.1093/mnrasl/slv013

X-ray coherent pulsations during a sub-luminous accretion disc state of the transitional millisecond pulsar XSS J12270−4859

A. Papitto,[1⋆] D. de Martino,[2] T. M. Belloni,[3] M. Burgay,[4] A. Pellizzoni,[4] A. Possenti[4] and D. F. Torres[1,5]

[1] *Institut de Ciències de l'Espai (IEEC-CSIC), Campus UAB, Fac. de Ciències, Torre C5, parell, 2a planta, E-08193 Barcelona, Spain*
[2] *INAF – Osservatorio Astronomico di Capodimonte, salita Moiariello 16, I-80131 Napoli, Italy*
[3] *INAF – Osservatorio Astronomico di Brera, via E Bianchi 46, I-23807 Merate (LC), Italy*
[4] *INAF – Osservatorio Astronomico di Cagliari, Via della Scienza, I-09047 Selargius (CA), Italy*
[5] *Institució Catalana de Recerca i Estudis Avançats (ICREA), E-08010 Barcelona, Spain*

Accepted 2015 January 20. Received 2015 January 20; in original form 2014 December 12

ABSTRACT

We present the first detection of X-ray coherent pulsations from the transitional millisecond pulsar XSS J12270−4859, while it was in a sub-luminous accretion disc state characterized by a 0.5–10 keV luminosity of 5×10^{33} erg s^{-1} (assuming a distance of 1.4 kpc). Pulsations were observed by *XMM–Newton* at an rms amplitude of (7.7 ± 0.5) per cent with a second harmonic stronger than the fundamental frequency, and were detected when the source is neither flaring nor dipping. The most likely interpretation of this detection is that matter from the accretion disc was channelled by the neutron star magnetosphere and accreted on to its polar caps. According to standard disc accretion theory, for pulsations to be observed the mass inflow rate in the disc was likely larger than the amount of plasma actually reaching the neutron star surface; an outflow launched by the fast rotating magnetosphere then probably took place, in agreement with the observed broad-band spectral energy distribution. We also report about the non-detection of X-ray pulsations during a recent observation performed while the source behaved as a rotationally-powered radio pulsar.

Key words: accretion, accretion discs – magnetic fields – stars: neutron – pulsars: individual: XSS J12270–4859 – stars: rotation – X-rays: binaries.

1 INTRODUCTION

The extremely short spin periods of millisecond pulsars (MSPs) are the outcome of a Gyr-long phase of accretion of mass transferred by a low-mass ($<\mathrm{M}_{\odot}$) companion star through an accretion disc (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). During the mass accretion phase these systems are bright X-ray sources. When mass transfer eventually declines, a pulsar powered by rotation of its magnetic field turns on, emitting from the radio to the gamma-ray band. The ∼300 radio MSPs in our Galaxy are then believed to be the recycled descendants of accreting neutron stars (NS) in low-mass X-ray binaries (NS-LMXBs). Indeed, accretion-powered pulsations at a period of few ms were detected from 15 NS-LMXBs, so far (Wijnands & van der Klis 1998), due to the channelling of the mass inflow to the magnetic poles of the NS by the magnetosphere. These sources are dubbed accreting millisecond pulsars (AMSPs; see Patruno & Watts 2012, for a review).

Recently, the tight link between MSPs and NS-LMXBs has been highlighted by the discovery of three transitional MSPs, sources that switched between accretion and rotation-powered emission on timescales ranging from a few weeks to a few years. These include, (i) IGR J18245–2452, a binary of the globular cluster M28 that turned on as a bright ($L_{\mathrm{X}} \approx 10^{36}$ erg s^{-1}) AMSP in 2013, and was observed as a rotationally-powered MSP a few years before, and a few weeks after the accretion event (Papitto et al. 2013); (ii) PSR J1023+0038, an MSP that had a sub-luminous ($\lesssim 10^{34}$ erg s^{-1}) accretion disc in 2000/2001 (Archibald et al. 2009), and that have entered back again in such a state in 2013 (Patruno et al. 2014; Stappers et al. 2014); (iii) XSS J12270−4859, an LMXB that remained for a decade in a sub-luminous disc accretion phase (Saitou et al. 2009; de Martino et al. 2010, 2013), characterized by correlated X-ray and UV flux variability (de Martino et al. 2013) and by bright radio and GeV emission (de Martino et al. 2010; Hill et al. 2011); during December 2012 it then transited to an MSP state characterized by the detection of 1.69 ms radio pulsations (Roy et al. 2014), a fainter X-ray and gamma-ray emission (Tam, Kong & Li 2013; Bassa et al. 2014; Bogdanov et al. 2014; Xing & Wang 2014), and the absence of an accretion disc (de Martino et al. 2014).

⋆ E-mail: papitto@ice.csic.es

Published by Oxford University Press on behalf of the Royal Astronomical Society

While only IGR J18245–2452 has been observed in a bright X-ray outburst so far, all the three transitional MSPs known showed a sub-luminous disc state (see e.g. Linares 2014). Such a state is characterized by (i) an accretion disc around the NS; (ii) a highly variable X-ray emission at a level of few × 10^{33} erg s^{-1}, intermediate between the luminosity shown by X-ray transients in outburst ($\gtrsim 10^{36}$ erg s^{-1}) and in quiescence ($\lesssim 10^{32}$ erg s^{-1}); (iii) a gamma-ray (>0.1 GeV) luminosity of few × 10^{33} erg s^{-1}, from two- to ten-times brighter with respect to the emission during the radio pulsar phase;[1] (iv) a radio continuum emission characterized by a flat spectrum, typical of outflows launched by compact objects in LMXBs. Such a complex phenomenology was interpreted in a number of studies in terms of an enshrouded radio MSP turned on in spite of the presence of the disc, producing high-energy radiation at the shock between the pulsar wind and the inflowing matter (Coti Zelati et al. 2014; Li et al. 2014; Stappers et al. 2014; Takata et al. 2014). On the other hand, Papitto, Torres & Li (2014) and Papitto & Torres (2014) proposed that matter penetrated inside the light cylinder turning off the rotationally-powered pulsar, while the system ejects matter from the inner disc boundary as a propeller.

Here we present an analysis of observations of XSS J12270−4859 performed by *XMM–Newton* in 2011 January and 2014 June, when the source was in the sub-luminous disc state and in the rotationally-powered state, respectively. This analysis was aimed at searching for a coherent signal by making use of the recently obtained radio pulsar ephemeris (Burgay et al., in preparation) derived from observations that have been performed during the rotationally-powered state in which the source is found since 2012 December.

2 OBSERVATIONS

XSS J12270−4859 was observed by *XMM–Newton* four times between 2009 and 2014. To search for a signal at the 1.69 ms spin period, we considered only the observations performed with the European Photon Imaging Camera (EPIC) pn operated in a fast timing mode with a time resolution of 29.5 µs, i.e. those performed on 2011 January 01 (Obs. Id 0656780901) and 2014 June 27 (Obs. Id 0729560801). In the first one the source was in a sub-luminous disc state, while in the latter the source behaved as a rotationally-powered radio MSP. During these observations the EPIC cameras were equipped with a thin optical blocking filter. Periods of high flaring background were identified during the 2014 observation and removed from the analysis, reducing the effective exposure to 39.4 ks, while the whole 30 ks exposure of the 2011 observation was retained. We analysed data using the *XMM–Newton* Science Analysis Software,[2] v. 14.0.

Source photons observed during the 2011 observation were extracted from an 86.1-arcsec-wide strip around the source position (equivalent to 21 pixels and enclosing 98 per cent of the energy), while the background was estimated from a strip of 12 arcsec of width, far from the source. As during the 2014 observation the source emission was dominated by background, we considered a smaller 45.1-arcsec-wide strip (enclosing 93 per cent of the energy). In order to estimate the source flux during this observation we considered data taken by the MOS cameras, which were operated in full window mode, thus retaining their imaging capabilities; a circular region of 50 arcsec of radius around the source position was considered to include 90 per cent of the photons emitted by the source, while the background was extracted from a 115 arcsec circular region without any source.

X-ray photons were preliminary reported to the Solar system barycentre using the position of the optical counterpart of XSS J12270−4859 determined by Masetti et al. (2006), RA = $12^{\mathrm{h}}27^{\mathrm{m}}58\overset{\mathrm{s}}{.}748$, Dec. = $-48^{\circ}53'42\overset{''}{.}88$.

3 ANALYSIS AND RESULTS

3.1 2011 observation

The light curve observed by the EPIC pn during the 2011 observation is plotted in Fig. 1. The source showed flaring activity during the last 4 ks of the observation (red points in Fig. 1), while during the remaining of the observation it was mostly found at a net count rate of ∼4.5 s^{-1} (steady quiescent state according to the terminology used in de Martino et al. 2013; see blue points in Fig. 1). This corresponds to an unabsorbed 0.5–10 keV flux of 2.1 × 10^{-11} erg cm^{-2} s^{-1}. Dips were also observed (green points in Fig. 1), and a threshold of 2 s^{-1} on the net count rate was used to distinguish between quiescent and dip emission. For details on the light curve and spectrum the reader is referred to de Martino et al. (2013).

In order to search for pulsations we used the pulsar ephemeris derived from a timing analysis of the radio pulsed signal detected during a series of observations performed with the Parkes 64 m antenna in 2014 (Burgay et al., in preparation; see central column of Table 1), and obtained assuming a circular orbit. Even if the spin-down rate of XSS J12270−4859 is not known, the typical rates observed from similar MSP (few × 10^{-15} Hz s^{-1}) ensured that only a single frequency had to be searched for pulsations in 2011 data. Caliandro, Torres & Rea (2012) estimated the amount of power lost, ϵ, when folding data with orbital parameters that are

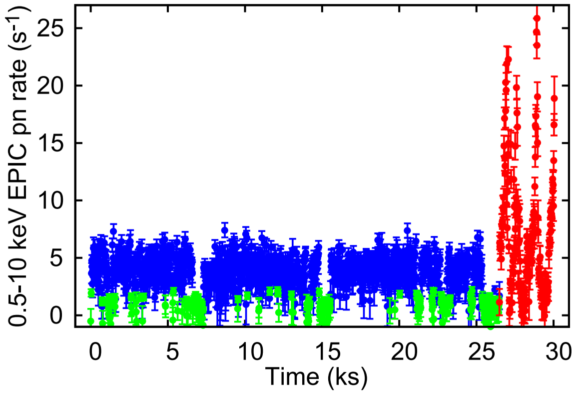

Figure 1. Background subtracted, 0.5–10 keV EPIC pn light curve observed on 2011 January 01. Quiescent, dip, and flaring state (see text for the definition) are plotted in blue, green, and red, respectively.

Table 1. Spin and orbital parameters of XSS J12270−4859.

Parameter	PKS (2014)	*XMM* (2011)
ν (Hz)	592.987 772 09(84)	592.987 771 24(35)
P_{orb} (s)	24 874.27(38)	–
$a \sin i/c$ (lt-s)	0.668 504(17)	–
T^{*} (MJD)	56718.1766(18)	55562.3121504(23)
T_{ref} (MJD)	56718.39814	55562.296372

---

[1] Note that gamma-ray emission from IGR J18245–2452 cannot be resolved as it belongs to a globular cluster.

[2] http://xmm.esac.esa.int/sas/

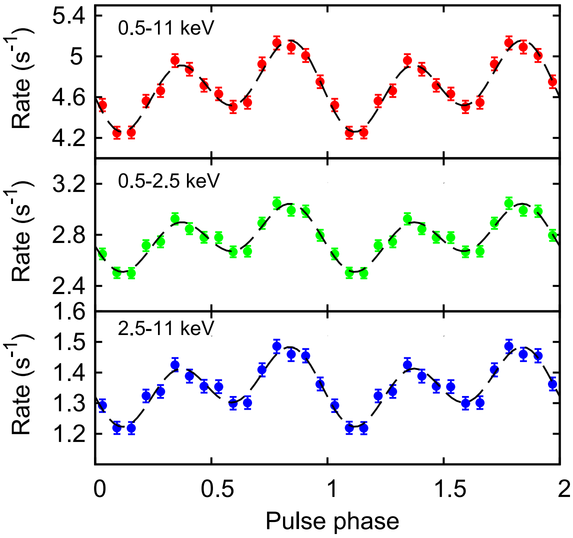

Figure 2. Background subtracted pulse profile observed during the steady quiescent state of the 2011 *XMM–Newton* observation in the 0.5–11 keV (top panel), 0.5–2.5 keV (middle panel), 2.5–11 keV (bottom panel) energy bands. Two cycles are shown for clarity.

different than the actual ones:

$$\delta(a\sin i/c) = \frac{1}{2\pi\nu}\frac{1}{\epsilon^2} \tag{1}$$

$$\delta T^* = \frac{0.1025 P_{\rm orb}}{\pi\nu(a\sin i/c)}\frac{1}{\epsilon^2} \tag{2}$$

$$\delta P_{\rm orb} = \frac{{P_{\rm orb}}^2}{2\pi\nu(a\sin i/c)\Delta T}\sqrt{\left(\frac{1-\epsilon^2}{10}\right)}. \tag{3}$$

Here, ν is the NS spin frequency, $a\sin i/c$ is the projected semimajor axis of the NS orbit, $P_{\rm orb}$ is the orbital period, and T^* is the epoch of the NS passage at the ascending node of the orbit. Considering the accuracy of the parameters of the radio timing solution, and setting $\epsilon = 0.8$, we concluded that only a search over plausible values of the epoch of passage at the ascending node of the orbit T^* (in steps of 3.2 s to cover an interval of 945 s) had to be performed. By folding X-ray data around the radio ephemeris and performing an epoch folding search, we found a coherent signal that had a statistical significance of 15σ after taking into account the number of trials made. The values we measured for the spin frequency and the epoch of passage at the ascending node are given in the rightmost column of Table 1; uncertainties were evaluated following Leahy (1987). During the steady quiescent state the signal had a root-mean-squared amplitude of $A_{\rm rms} = (7.7 \pm 0.5)$ per cent (corrected for the background), and was modelled by two harmonic components, with the second harmonic stronger by a factor $\simeq$1.8 than the fundamental frequency (see top panel of Fig. 2). The shape of the pulse profile was similar in a soft (0.5–2.5 keV) and a hard (2.5–11 keV) energy band, with an rms amplitude of (6.1 ± 0.9) and (7.5 ± 0.7) per cent, respectively (see middle and bottom panel of Fig. 2). The phase of the second harmonic varied over intervals of 5 ks while the phase of the first one was stable within the errors, indicating slight changes of the pulse profile during the steady quiescent state (see Fig. 3); no residual variability at the orbital period was found.

The variance of the pulse profile obtained by folding the X-ray photons observed during the dipping and the flaring activity has a probability of being produced by photon counting noise of 5.8 and 2.7 per cent, respectively. We then set upper limits on the background corrected rms amplitude observed during the dipping and the flaring state of 5.9 and 2.0 per cent (3σ confidence level), respectively. If pulsations were present during these states, their amplitude was then lower than during the steady quiescent state.

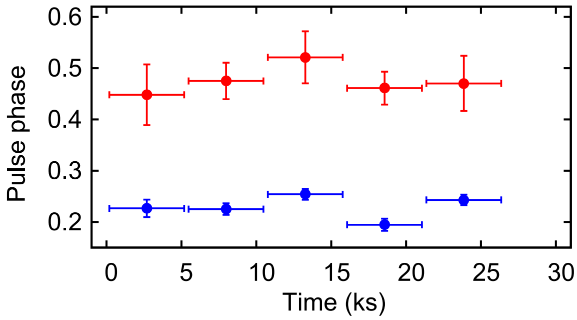

Figure 3. Phase of the first (red points, top) and second harmonic (blue points, bottom) observed during the steady quiescent state.

3.2 2014 observation

During the 2014 observation XSS J12270−4859 was in a rotationally-powered state. It was much fainter in X-rays than in 2011, as it could not be detected at its position in the one-dimensional image of the EPIC pn chip due to the contribution of close-by sources. To evaluate the source flux we extracted a spectrum from data taken by the two MOS cameras. The spectrum in the 0.3–10 keV energy range was modelled with a power law with an index of $\Gamma = 1.07(7)$, giving a 0.5–10 keV flux of $7.0(5) \times 10^{-13}$ erg cm^{-2} s^{-1}. We evaluated with WEBPIMMS[3] the count rate expected for the EPIC pn as 0.15 s^{-1}. Such a count rate gives an expected signal-to-noise ratio of unity in the 45.1-arcsec-wide stripe of the EPIC pn chip that we used to extract photons. Folding the observed X-ray photons around the radio pulsar ephemeris, and performing a search on possible values of the epoch of passage at the ascending node analogous to that carried out on 2011 data, did not result in significant detection. We set an upper limit on the background subtracted rms amplitude of 7.1 per cent (3σ confidence level). The signal was not detected even in the 0.5–2.5 keV range in which X-ray pulsations were detected by Archibald et al. (2009) from the twin MSP PSR J1023+0038. We set an upper limit at a 3σ confidence level on the rms amplitude of 9.8 per cent. Similar results were obtained when searching for a signal at the second harmonic of the signal. During the observation of June 2014, XSS J12270−4859 showed an orbital modulation with an amplitude of $\approx$70 per cent, similar to that already observed by Bogdanov et al. (2014) in an *XMM–Newton* observation performed in December 2013. While a detailed analysis of the orbital characteristics will be presented elsewhere, a search for pulsations restricted to orbital phases close to superior conjunction (i.e. when the pulsar contribution to the X-ray emission is expected to be larger) gave an upper limit of 14 per cent on the rms amplitude.

4 DISCUSSION

We reported the first detection of X-ray pulsation at the 1.69 ms spin period from XSS J12270−4859 while it was in a sub-luminous disc state. Considering the enigmatic nature of such a state, both a rotationally- and an accretion-powered origin are considered next.

---

[3] https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl

4.1 Rotationally-powered pulsations

The spin-down power of XSS J12270−4859 measured by Roy et al. (2014) during the rotationally-powered MSP state is 0.9×10^{35} erg s^{-1}. A fraction equal to 10^{-3} of this power is converted into observed 0.5–10 keV X-rays, similar to other rotationally-powered MSPs (Possenti et al. 2002). If XSS J12270−4859 were rotationally powered also during the sub-luminous accretion disc state, an X-ray luminosity of $\approx 10^{32}$ erg s^{-1} would be then expected. The 0.5–10 keV luminosity observed in 2011 is instead much larger, $L_{\rm X} \simeq 5 \times 10^{33}$ erg s^{-1} (assuming a distance of 1.4 kpc, as estimated by Roy et al. 2014 from the dispersion measure of radio pulses). Even if only the pulsed luminosity, $\sqrt{2}A_{\rm rms}L_x \simeq 5 \times 10^{32}$ erg s^{-1}, had a magnetospheric origin, XSS J12270−4859 would still have been five times overluminous in X-rays than during the rotationally-powered MSP state. Furthermore, we set an upper limit on the 0.5–10 keV pulsed luminosity during the 2014 rotationally-powered pulsar state of $\simeq 1.6 \times 10^{31}$ erg cm^{-2} s^{-1}, which is $\sim$30 times smaller than the value observed during the 2011 sub-luminous disc state. If pulsations observed during the sub-luminous disc state were of magnetospheric origin, one would not expect such a strong variation of the X-ray pulsed flux when the source switches to a purely rotationally-powered state. Together with the previous energetic considerations, this disfavours an interpretation of the pulses being produced by a rotationally-powered MSP.

4.2 Accretion-powered pulsations

The X-ray pulsations observed from XSS J12270−4859 closely resemble those observed from AMSPs, which have an amplitude of few per cent, and are modelled with two harmonics (see Patruno 2012, and references therein). The second harmonic of the pulse observed from XSS J12270−4859 is stronger than the fundamental frequency; a similar shape was observed from the pulses of the eclipsing AMSP, SWIFT J1749.4−2807 (Altamirano et al. 2011; Ferrigno et al. 2011). According to analytical calculations made by Poutanen & Beloborodov (2006), the ratio of the amplitude of the second harmonic to the fundamental observed from a fast pulsar whose antipodal spots are always visible, is $c_2/c_1 = 1/2(\tan i \tan\theta)$, where i is the binary inclination and θ is the spot colatitude. de Martino et al. (2014) constrained the inclination of XSS J12270−4859 between 45° and 65° from the modelling of the optical light curve observed during the rotationally-powered state. The large ratio observed in the case of XSS J12270−4859, $c_2/c_1 \simeq 1.8$, then indicates a large spot colatitude, $\theta \gtrsim 60^\circ$.

X-ray pulsations were observed from XSS J12270−4859 at a 0.5–10 keV luminosity of $\simeq 5 \times 10^{33}$ erg s^{-1}, more than an order of magnitude lower than the level at which pulses have been observed from AMSPs so far ($\approx 10^{35}$ erg s^{-1}; Patruno et al. 2009). Accretion on to the NS surface occurs unhindered as long as the disc is truncated within the corotation radius, $R_{\rm co} = 23.7\, m_{1.4}^{1/3}$ km for XSS J12270−4859, where $m_{1.4}$ is the NS mass in units of 1.4 M$_\odot$. The radius at which the magnetosphere truncates the disc is expressed as a fraction $\xi = 0.5$–1 of the Alfvén radius (see e.g. Ghosh 2007), $R_{\rm in} \simeq 116\, \xi\, \dot{m}_{14}^{-2/7}\, m_{1.4}^{-1/7}\, \mu_{26}^{4/7}$ km, where $\dot{m}_{14}$ is the disc mass inflow rate in units of 10^{14} g s^{-1}, and μ_{26} is the NS dipole magnetic moment in units of 10^{26} G cm^{-3}. We estimate $\mu_{26} = 0.8$ for XSS J12270−4859 by using the relation given by Spitkovsky (2006) to derive the NS dipole magnetic moment from the spin-down power, and considering the limiting case of a purely orthogonal rotator (i.e. $\theta = 90^\circ$; larger values of μ are obtained for a smaller magnetic inclination angle). In the 10–100 keV band XSS J12270−4859 emitted a luminosity comparable to that observed in the 0.5–10 keV band (de Martino et al. 2010), giving a bolometric X-ray luminosity of $L_{\rm X} \simeq 10^{34}$ erg s^{-1}. Assuming that the whole accretion power is converted into observable X-ray emission, we then estimate that while X-ray pulsations were observed, $\dot{m}_{14} \simeq 0.5$. Considering such a mass accretion rate, the disc should have been truncated at $R_{\rm in} \gtrsim 60$ km (evaluated for $\xi = 0.5$ and $m_{1.4} = 1$), approximately three times larger than the corotation radius. Accretion on to the NS surface should have been then completely inhibited by the centrifugal barrier set by the quickly rotating magnetosphere of the NS, contrasting with the observations of accretion-driven X-ray pulsations.

4.3 An evidence of mass outflow?

A disc mass accretion rate larger than the value deduced from the observed X-ray luminosity is an intriguing possibility to reconcile the observation of X-ray pulsation with standard disc accretion theory. A larger disc inward pressure would in fact allow the inner disc radius to lie close to the corotation surface. To satisfy $R_{\rm in} = R_{\rm co}$, a mass accretion rate $\dot{m}_{14}$ ranging between 15 and 160 (for ξ in the range 0.5–1 and $m_{1.4} = 1$) is needed. A similar accretion rate is larger by a factor $\gtrsim$30 than that implied by the X-ray luminosity. More than 95 per cent of the inflowing disc mass should be then ejected by the system close to the magnetospheric boundary.

The possibility that an outflow is launched by XSS J12270−4859 in the sub-luminous disc state is compatible with the flat (or slightly inverted) bright radio emission (Hill et al. 2011), which is typical of outflowing LMXBs. Outflows can be launched by a fast rotating MSP due to the propeller effect (Illarionov & Sunyaev 1975). Papitto et al. (2014) applied a similar scenario to explain the X-ray and gamma-ray emission observed from XSS J12270−4859 in the disc sub-luminous state in terms of synchrotron and self-synchrotron Compton emission emitted at the disc–magnetosphere boundary. We note that XSS J12270−4859 (as later also PSR J1023+0038, see below) is the first confirmed accreting NS to show a bright gamma-ray output.

If the disc mass inflow rate is more than 30 times larger than the rate indicated by the X-ray luminosity, it also follows that the X-ray radiative efficiency of the accretion disc (which emits half of the accretion power liberated down to that distance) should be of less than 20 per cent, in order to match the observed X-ray luminosity. Such a low disc X-ray radiative efficiency is of the order of that recently estimated by D'Angelo et al. (2014) for Cen X-4. Accretion discs are expected to become radiatively inefficient as soon as the mass inflow rate drops below $\dot{m}_{14} \approx 500$ (e.g. Done, Gierliński & Kubota 2007), a value compatible with the that observed from XSS J12270−4859.

According to the so-called radio-ejection scenario (Burderi et al. 2001), the pressure of the rotating NS magneto-dipole is also a possible driver of ejection of mass from a system hosting an MSP. Since the observation of X-ray pulsations is a strong indication that mass accretes on to the NS surface, applying the radio-ejection scenario to the case of XSS J12270−4859 requires the assumption that the pressure of the magneto-dipole radiation is able to eject matter even if a significant fraction of the matter inflow manages to enter the light cylinder. This could be the case if the pressure exerted by the magneto-dipole radiation is not isotropic (e.g. flowing preferentially along the magnetic equatorial plane), and the magnetic axis of the dipole is significantly offset with respect to the spin axis (and then lies close to the disc orbital plane), as indicated by the very strong second harmonic seen in the pulse profile.

4.4 A comparison with PSR J1023+0038

During the preparation of this manuscript, Archibald et al. (2014) reported the detection of X-ray pulsations from PSR J1023+0038 in a similar sub-luminous disc accretion state as the one in which we detected pulsations from XSS J12270−4859. Pulsations were detected only during quiescent emission (which they dubbed *high state*), while not during dips (*low state* according to their terminology), nor during flares. They also interpreted X-ray pulsations in terms of channelled accretion on to the NS surface.

The detection of accretion-powered pulsations from both these systems rules out the possibility that a radio MSP was active during the sub-luminous disc state. If it were the case the accretion disc should have been truncated beyond the light cylinder (80 km for these two sources), which is larger than the corotation radius, thus preventing accretion on to the NS surface. The X-ray luminosity of PSR J1023+0038 when it showed pulsations was similar to that shown by XSS J12270−4859 and similar considerations can be made on the value of the disc mass accretion rate needed to keep the disc inner boundary within the corotation surface, and on the occurrence of outflows. Quite interestingly, also the pulse profile shown by PSR J1023+0038 in the sub-luminous disc state is remarkably similar to that shown by XSS J12270−4859. The inclination of PSR J1023+0038 is relatively low, $\lesssim 55^\circ$ (Thorstensen & Armstrong 2005; Wang et al. 2009), and also in that case a large spot colatitude is requested to yield a comparable power in the first and the second harmonic of the signal. It remains to be understood whether a magnetic field configuration with spots close to the equator, which seems to be relevant to both XSS J12270−4859 and PSR J1023+0038, might influence the uncommon properties that they showed in the sub-luminous disc state.

ACKNOWLEDGEMENTS

AP and DFT acknowledge support from the grants AYA2012-39303 and SGR 2014-1073. AP is supported by a Juan de la Cierva fellowship. DdM acknowledges financial support from ASI/INAF I/037/12/0. TMB acknowledges support from INAF PRIN 2012-6. Based on observations obtained with *XMM–Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. We gratefully thank Dr Norbert Schartel and the ESAC staff for their help in obtaining the *XMM–Newton* data.

REFERENCES

Alpar M. A., Cheng A. F., Ruderman M. A., Shaham J., 1982, Nature, 300, 728
Altamirano D. et al., 2011, ApJ, 727, L18
Archibald A. M. et al., 2009, Science, 324, 1411
Archibald A. M. et al., 2014, preprint (arXiv:1412.1306)
Bassa C. G. et al., 2014, MNRAS, 441, 1825
Bogdanov S., Patruno A., Archibald A. M., Bassa C., Hessels J. W. T., Janssen G. H., Stappers B. W., 2014, ApJ, 789, 40
Burderi L. et al., 2001, ApJ, 560, L71
Caliandro G. A., Torres D. F., Rea N., 2012, MNRAS, 427, 2251
Coti Zelati F., Campana S., D'Avanzo P., Melandri A., 2014, MNRAS, 438, 2634
D'Angelo C. R., Fridriksson J. K., Messenger C., Patruno A., 2014, preprint (arXiv:1410.3760)
de Martino D. et al., 2010, A&A, 515, A25
de Martino D. et al., 2013, A&A, 550, A89
de Martino D. et al., 2014, MNRAS, 444, 3004
Done C., Gierliński M., Kubota A., 2007, ARA&A, 15, 1
Ferrigno C., Falanga M., Bozzo E., Becker P. A., Klochkov D., Santangelo A., 2011, A&A, 532, A76
Ghosh P., 2007, Rotation and Accretion Powered Pulsars. World Scientific Press, Singapore
Hill A. B. et al., 2011, MNRAS, 415, 235
Illarionov A. F., Sunyaev R. A., 1975, A&A, 39, 185
Leahy D. A., 1987, A&A, 180, 275
Li K. L., Kong A. K. H., Takata J., Cheng K. S., Tam P. H. T., Hui C. Y., Jin R., 2014, ApJ, 797, 111
Linares M., 2014, ApJ, 795, 72
Masetti N. et al., 2006, A&A, 459, 21
Papitto A., Torres D. F., 2014, submitted
Papitto A. et al., 2013, Nature, 501, 517
Papitto A., Torres D. F., Li J., 2014, MNRAS, 438, 2105
Patruno A., 2012, ApJ, 753, L12
Patruno A., Watts A. L., 2012, preprint (arXiv:1206.2727)
Patruno A., Watts A., Klein Wolt M., Wijnands R., van der Klis M., 2009, ApJ, 707, 1296
Patruno A. et al., 2014, ApJ, 781, L3
Possenti A., Cerutti R., Colpi M., Mereghetti S., 2002, A&A, 387, 993
Poutanen J., Beloborodov A. M., 2006, MNRAS, 373, 836
Radhakrishnan V., Srinivasan G., 1982, Curr. Sci., 51, 1096
Roy J. et al., 2014, ApJ, preprint (arXiv:1412.4735)
Saitou K., Tsujimoto M., Ebisawa K., Ishida M., 2009, PASJ, 61, L13
Spitkovsky A., 2006, ApJ, 648, L51
Stappers B. W. et al., 2014, ApJ, 790, 39
Takata J. et al., 2014, ApJ, 785, 131
Tam P. H. T., Kong A. K. H., Li K. L., 2013, Astron. Telegram, 5652, 1
Thorstensen J. R., Armstrong E., 2005, AJ, 130, 759
Wang Z., Archibald A. M., Thorstensen J. R., Kaspi V. M., Lorimer D. R., Stairs I., Ransom S. M., 2009, ApJ, 703, 2017
Wijnands R., van der Klis M., 1998, Nature, 394, 344
Xing Y., Wang Z., 2014, preprint (arXiv:1411.3449)

This paper has been typeset from a TEX/LATEX file prepared by the author.