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

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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 disk state characterized by a 0.5–10 keV luminosity of $5 \times 10^{33}$ 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)% 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 disk was channelled by the neutron star magnetosphere and accreted onto its polar caps. According to standard disk accretion theory, for pulsations to be observed the mass infall rate in the disk 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 -- pulsars: XSS J12270–4859 -- stars: neutron -- stars:rotation — X-rays: binaries

1 INTRODUCTION
The extremely short spin periods of millisecond pulsars are the outcome of a Gyr-long phase of accretion of mass transferred by a low mass ($< M_\odot$) companion star through an accretion disk (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 millisecond radio pulsars (MSP) in our Galaxy are then believed to be the recycled descendants of accreting neutron stars (NS) in low mass X-ray binaries (NS-LMXB). 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 in-flow to the magnetic poles of the NS by the magnetosphere. These sources are dubbed accreting millisecond pulsars (AMSP, 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 ms pulsars, sources that switched between accretion and rotation-powered emission on time scales 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 ($L_X \approx 10^{36}$ 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 disk 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 disk 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. 2014; 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 et al. 2013; Bassa et al. 2014; Bogdanov et al. 2014; Xing & Wang 2014), and the absence of an accretion disk (de Martino et al. 2014).

While only IGR J18245–2452 has been observed in a bright X-ray outburst so far, all the three transitional ms pulsars known showed a sub-luminous disk state (see, e.g. Linares 2014). Such a
state is characterized by (i) an accretion disk around the NS; (ii) a highly variable X-ray emission at a level of \( \times 10^{33} \text{ erg s}^{-1} \), intermediate between the luminosity shown by X-ray transients in outburst (\( \geq 10^{35} \text{ erg s}^{-1} \)) and in quiescence (\( \leq 10^{35} \text{ erg s}^{-1} \)); (iii) a gamma-ray (\( > 0.1 \text{ GeV} \)) luminosity of \( \times 10^{35} \text{ erg s}^{-1} \), from two- to ten-times brighter with respect to the emission during the radio pulsar phase; (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 disk, producing high-energy radiation at the shock between the pulsar wind and the in-flowing matter (Stappers et al. 2014; Takata et al. 2014; Coti Zelati et al. 2014; Li et al. 2014). On the other hand, Papitto et al. (2014) and Papitto & Torres (2014, submitted) proposed that matter penetrated inside the light cylinder turning off the rotationally-powered pulsar, while the system ejects matter from the inner disk boundary as a propeller.

Here we present an analysis of observations of XSS J12270–4859 performed by XMM-Newton in January 2011 and June 2014, when the source was in the sub-luminous disk 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 prep.) derived from observations that have been performed during the rotationally-powered state in which the source is found since December 2012.

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 EPIC-pn camera operated in a fast timing mode with a time resolution of 29.5 \( \mu \text{s} \), i.e. those performed on 2011 Jan 01 (Obs. Id 0656780901) and 2014 Jun 27 (Obs. Id 0729560801). In the first one the source was in a sub-luminous disk 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 analyzed data using the XMM-Newton Science Analysis Software (SAS) v. 14.0.

Source photons observed during the 2011 observation were extracted from an 86.1\(^\circ\)-wide strip around the source position (equivalent to 21 pixels and enclosing 98\% of the energy), while the background was estimated from a strip of 12\" of width, far from the source. As during the 2014 observation the source emission was dominated by background, we considered a smaller 45.1\(^\circ\)-wide strip (enclosing 93\% 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\" of radius around the source position was considered to include 90\% of the photons emitted by the source, while the background was extracted from a 115\" 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\(^{\circ}\) 27\(^{m}\) 58.748\(^{s}\), DEC=−48\(^{\circ}\) 53’ 42.88”.

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 countrate of \( \sim 4.5 \text{ s}^{-1} \) (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 \( 2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \). Dips were also observed (green points in Fig. 1), and a threshold of \( 2 \text{ s}^{-1} \) 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 prep.; 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 \( \times 10^{-15} \text{ Hz s}^{-1} \)) ensured that only a single frequency had to be searched for pulsations in 2011 data. [Caliandro et al. 2012] estimated the amount of power lost \( \epsilon \) when folding data with orbital parameters that are different than the actual ones:

\[
\delta(a \sin i/c) = \frac{1}{2\pi n} \frac{1}{e^2} \quad (1)
\]

\[
\delta T^* = \frac{0.1025 P_{\text{orb}}}{n \pi (a \sin i/c)} \frac{1}{e^2} \quad (2)
\]

\[
\delta P_{\text{orb}} = \frac{P_{\text{orb}}^2}{2\pi (a \sin i/c) \Delta t} \sqrt{\frac{1-e^2}{10}} \quad (3)
\]

Here, \( \nu \) is the NS spin frequency, \( a \sin i/c \) is the projected semi-major axis of the NS orbit, \( P_{\text{orb}} \) 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 15-$\sigma$ 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 (1983). During the steady quiescent state the signal had at a root mean-squared amplitude of $A_{\text{rms}} = (7.7 \pm 0.5)\%$ (corrected for the background), and was modelled by two harmonic components, with the second harmonic stronger by a factor $\approx 1.8$ than the fundamental frequency (see top panel 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 rms amplitude of $(6.1 \pm 0.9)\%$ and $(7.5 \pm 0.7)\%$, 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. 2). 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%, respectively. We then set upper limits on the background contribution of data taken by the two MOS cameras. The spectrum in the 0.5-11 keV energy range was modelled with a power law with an index of $0.3-10$ keV energy range was modelled with a power law with an index of $0.3-10$ keV, and 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 3-$\sigma$ confidence level on the rms amplitude of 9.8%. 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 $\approx 70\%$, 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% on the rms amplitude.

### Table 1. Spin and orbital parameters of XSS J12270–4859

| Parameter | PKS (2014) | XMM (2011) |
|-----------|------------|------------|
| $\nu$ (Hz) | 592.9877720(84) | 592.98777124(35) |
| $P_{\text{orb}}$ (s) | 24874.27(38) | ... |
| $a \sin i/c$ (lt-s) | 0.668504(17) | ... |
| $T^*$ (MJD) | 56718.1766(18) | 55562.3121504(23) |
| $T_{\text{ref}}$ (MJD) | 56718.39814 | 55562.296372 |

### 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.

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

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

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3 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.pl the countrate 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"-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 a upper limit on the background subtracted rms amplitude of 7.1% (3-$\sigma$ 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 3-$\sigma$ confidence level on the rms amplitude of 9.8%. 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 $\approx 70\%$, 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% 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 disk state. Considering the enigmatic nature of such a state, both a rotationally and an accretion-powered origin are considered next.

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 \(0.9 \times 10^{35}\) 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 disk state, an X-ray luminosity of \(10^{32}\) erg s\(^{-1}\) would then be expected. The 0.5–10 keV X-ray luminosity observed in 2011 is instead much larger, \(L_X \approx 5 \times 10^{33}\) 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, \(\sqrt{2}A_{\text{in}}L_\text{p} \approx 5 \times 10^{32}\) 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 \(1.6 \times 10^{34}\) cm\(^{-2}\) s\(^{-1}\), which is \(\approx 30\) times smaller than the value observed during the 2011 sub-luminous disk state. If pulsations observed during the sub-luminous disk 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 2005, the ratio of the amplitude of the second harmonic to the fundamental observed from a fast pulsar whose antipodal spots are always visible, is \(c_2/c_1 = 1/2(\tan \iota_1 / \tan \iota_2)\), where \(i\) is the binary inclination and \(\theta\) is the spot co-latitude (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, \(c_2/c_1 \approx 1.8\) then indicates a large spot co-latitude, \(\theta \approx 60°\).

X-ray pulsations were observed from XSS J12270–4859 at a 0.5–10 keV luminosity of \(\approx 5 \times 10^{33}\) 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 onto the NS surface occurs unhindered as long as the disk is truncated within the co-rotation radius, \(R_{\text{in}} = 23.7 m_{\text{ns}}^{1/4}\) km for XSS J12270–4859, where \(m_{\text{ns}}\) is the NS mass in units of 1.4 M\(_\odot\). The radius at which the magnetosphere truncates the disk is expressed as a fraction \(\xi = 0.5 – 1\) of the Alfvén radius (see, e.g., Ghosh 2007). \(R_{\text{in}} \approx 116 \xi m_{\text{ns}}^{1/4} m_{1.4}^{1/7} c_{26}^{3/7}\) km, where \(m_{1.4}\) is the disk mass in-flow rate in units of \(10^{14}\) g s\(^{-1}\), and \(\mu_{26}\) is the NS dipole magnetic moment in units of \(10^{36}\) 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., \(\theta = 90°\); larger values of \(\mu\) 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. 2014), giving a bolometric X-ray luminosity of \(L_X \approx 10^{35}\) 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, \(m_{14} \approx 0.5\). Considering such a mass accretion rate, the disk should have been truncated at \(R_{\text{in}} \approx 60\) km (evaluated for \(\xi = 0.5\) and \(m_{14} = 1\)), approximately three times larger than the co-rotation radius. Accretion onto 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 disk 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 disk accretion theory. A larger disk inward pressure would in fact allow the inner disk radius to lie close to the co-rotation surface. To satisfy \(R_{\text{in}} = R_{\text{co}}\), a mass accretion rate \(\dot{m}_{14}\) ranging between 15 and 160 (for \(\xi = 0.5\) and \(m_{14} = 1\)) is needed. Such a similar accretion rate is larger by a factor \(\approx 30\) than that implied by the X-ray luminosity. More than 95% of the in-flowing disk mass should then be ejected by the system close to the magnetospheric boundary.

The possibility that an outflow is launched by XSS J12270–4859 in the sub-luminous disk 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 millisecond pulsar 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 disk sub-luminous state in terms of synchrotron and self-synchrotron Compton emission emitted at the disk-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 disk mass in-flow 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 disk (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 disk X-ray radiative efficiency is of the order of that recently estimated by D’Angelo et al. 2014 for Cen X-4. Accretion disks are expected to become radiatively inefficient as soon as the mass in-flow rate drops below \(\dot{m}_{14} \approx 500\) (e.g., Done et al. 2007), a value compatible with that observed from XSS J12270–4859.

According to the so-called radio-ejection scenario (Burderi et al. 2001), the pressure of the rotating NS magnetodipole is also a possible driver of ejection of mass from a system hosting a MSP. Since the observation of X-ray pulsations is a strong indication that mass accretes onto the NS surface, applying the radio-ejection scenario to the case of XSS J12270–4859 requires the assumption that the pressure of the magnetodipole radiation is able to eject matter even if a significant fraction of the
matter in-flow 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 disk 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 disk 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 onto 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 disk state. If it were the case the accretion disk should have been truncated beyond the light cylinder (80 km for these two sources), which is larger than the corotation radius, thus preventing accretion onto the NS surface. The X-ray luminosity of PSR J1023+0038 when its showed pulsations was similar to that shown by XSS J12270–4859 and similar considerations can be made on the value of the disk mass accretion rate needed to keep the disk inner boundary within the co-rotation surface, and on the occurrence of outflows. Quite interestingly, also the pulse profile shown by PSR J1023+0038 in the sub-luminous disk 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 co-latitude 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 disk state.

ACKNOWLEDGEMENTS

AP and DFT acknowledge support from the 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.

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