PSR J0737–3039: INTERACTING PULSARS IN X-RAYS

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ABSTRACT

We present the results of a ~230 ks long X-ray observation of the relativistic double pulsar system PSR J0737–3039 obtained with the XMM-Newton satellite in 2006 October. We confirm the detection in X-rays of pulsed emission from PSR A, mostly ascribed to a soft non-thermal power-law component ($\Gamma \sim 3.3$) with a 0.2–3 keV luminosity of $\sim 1.9 \times 10^{30}$ erg s$^{-1}$ (assuming a distance of 500 pc). For the first time, pulsed X-ray emission from PSR B is also detected in part of the orbit. This emission, consistent with thermal radiation with temperature $kT_B \approx 30$ eV and bolometric luminosity of $\sim 10^{32}$ erg s$^{-1}$, is likely powered by heating of PSR B’s surface caused by PSR A’s wind. A hotter ($\sim 130$ eV) and fainter ($\sim 5 \times 10^{29}$ erg s$^{-1}$) thermal component, probably originating from back-falling particles heating polar caps of either PSR A or PSR B or is also required by the data. No signs of X-ray emission from a bow-shock between PSR A’s wind and the interstellar medium or PSR B’s magnetosphere are present. The upper limit on the luminosity of such a shock component ($\sim 10^{29}$ erg s$^{-1}$) constrains the wind magnetization parameter $\sigma_M$ of PSR A to values greater than 1.

Subject headings: binaries: general – stars: neutron – pulsars: general – pulsars: individual (PSR J0737–3039A, PSR J0737–3039B) – X-rays: stars – radiation mechanisms: general

1. INTRODUCTION

The short-period, double radio pulsar system PSR J0737–3039 (Burgay et al. 2003; Lyne et al. 2004), besides being of paramount interest as a probe for theories of strong field gravity (Kramer et al. 2006), represents a unique laboratory for studies in several fields, ranging from the equation of state of super-dense matter to magnetohydrodynamics. The system is observed nearly edge-on and consists of a fast, recycled radio pulsar (PSR A, period $P = 22.7$ ms) orbiting its slower companion (PSR B, $P = 2.77$ s) with an orbital period of only 2.4 hours. Radio observations of the two pulsars permit to derive a wealth of information which is not available for other neutron stars. These obviously include the neutron star masses and all the other geometrical and dynamical parameters of the system, but also information on the structure and physical properties of the two magnetospheres. The double pulsar is rich in observational phenomena, including a short radio eclipse of A by B and orbital modulation of the radio flux of B due to the influence of A (Lyne et al. 2004). The individual pulses from B show drifting features due to the impact of the low-frequency electromagnetic wave in the relativistic wind from A (McLaughlin et al. 2004a), while the eclipse of A is modulated at half the rotational period of B (McLaughlin et al. 2004a).

High-energy observations are an important complement to these studies, in particular for what concerns the physics of the magnetospheric emission and dissipative shocks in the close environment of the two neutron stars.

X-rays could be pulsed magnetospheric or thermal emission from pulsar A, as seen for several other recycled pulsars (Zavlin et al. 2002), but they could also originate in the colliding winds of A and B (Lyutikov 2004). Due to the interaction of the relativistic wind of the fast spinning pulsar A ($E_{\text{rot}} = 5.8 \times 10^{33}$ erg s$^{-1}$) with the magnetosphere of its much less energetic companion ($E_{\text{rot}}^B = 1.6 \times 10^{30}$ erg s$^{-1}$), the formation of a bow-shock, likely emitting at high energies, is expected. The predicted fluxes are roughly comparable to those observed for magnetospheric and/or surface emission from the pulsars. A termination shock between the two pulsars can probe the properties of a pulsar’s relativistic wind at a smaller distance from the central engine than ever studied before. Additionally, detection of an orbital phase dependence in the X-ray emission might be expected (Lyutikov 2004; Arons & Tavani 1993). Such variability could constrain the geometry of the emission site, thus providing new insights into the wind physics close to the pulsar. Alternatively, most of the high-energy emission could arise from the shock generated when one or both the pulsar winds interact with the interstellar medium (Granot & Meszaros 2004).

The first X-ray observation of PSR J0737–3039, a short (10 ks) Chandra pointing (McLaughlin et al. 2004a) yielded only ~80 photons. The low X-ray luminosity ($L_X = 2 \times 10^{30} d_{\text{5 kpc}}^2$ erg s$^{-1}$, where we indicate with $d_{\text{5 kpc}}$ the distance in units of 5 kpc) corresponds roughly to the entire spin-down luminosity of the slow pulsar B and to only a small fraction of that of pulsar A. The Chandra data of this pioneer observation could only poorly constrain the source spectrum, which appeared quite soft,
and cannot provide significant evidence for variability, due to the small statistics and time resolution insufficient to look for the spin periods of the two pulsars.

A longer public observation (50 ks), carried out in March 2004 through the XMM-Newton Director’s Discretionary Time program, yielded an improvement in statistics by a factor ~10 with respect to the first look of Chandra. These data confirmed the softness of the spectrum, which could be fit either by a power-law with photon index $\Gamma = 3.5^{+0.3}_{-0.3}$ and absorption $N_{\text{H}} \approx 7.0 \times 10^{20}$ cm$^{-2}$, or by a blackbody with temperature of 0.15 keV and a lower interstellar absorption (Pellizzoni et al. 2004). These authors could also perform the first X-ray timing analysis for PSR J0737–3039, but no periodic or aperiodic variations were found, with upper limits of ~60% on the pulsed fractions of both pulsars, and of ~40% for modulations at the orbital period (all limits are at 99% c.l. and for sinusoidal light curves). Campana et al. (2004) reported a joint spectral analysis of the XMM-Newton (only the MOS) and Chandra data, reaching similar conclusions on the source spectrum.

A further Chandra observation (~90 ks) with the High Resolution Camera (HRC-S) showed X-ray pulses at the period of PSR A (Chatterjee et al. 2007), with a double peaked profile, similar to that observed in radio, and a pulsed fraction of ~70%. Although purely non-thermal emission is consistent with the data, the X-ray pulse morphology of PSR A, in combination with previously reported spectral properties of the X-ray emission, suggests the existence of both non-thermal magnetospheric emission and a broad sinusoidal thermal emission component from the neutron star surface. No pulsations were detected from pulsar B, nor evidence for orbital modulation.

Here we report the results of a ~230 ks long X-ray observation of PSR J0737–3039 obtained within the frame of XMM-Newton “Large Programs” in October 2006.

2. X-RAY OBSERVATION AND DATA REDUCTION

Our observation of PSR J0737–3039 was carried out in two consecutive XMM-Newton orbits. The first part of the observation started on 2006, October 26th at 00:28:15 UT and lasted 119.8 ks, the second one started on October 28th at 00:28:37 UT and lasted 114.5 ks. In total, the observation allowed the coverage of ~26 revolutions of the binary system ($P_{\text{orb}} = 8.834.535$ s). The pn camera (Strüder et al. 2001) was operated in Small Window mode (imaging across a $4' \times 4'$ field of view with a 5.67 ms time resolution) with the medium optical filter. The MOS cameras (Turner et al. 2001) were also set in the Small Window mode (yielding a $2' \times 2'$ field of view in the central CCD, with a time resolution of 0.3 s) with the medium filter. The data were processed using standard pipeline tasks (EMPROC and EPPROC) of the XMM-Newton Science Analysis Software (SAS) version 7.1.0.

In view of the faintness of PSR J0737–3039 in soft X-rays, a particular care in selecting source photons and reducing background contamination is crucial. We used only photons with pattern 0–12 for the MOS cameras, while for the pn we used pattern 0–4 for energies above 0.4 keV and pattern 0 for the $E < 0.4$ keV energy range. Such an event selection allows to reduce by a factor ~3.5 the background count rate in the 0.15–0.4 keV energy range in the pn camera, while leaving almost unchanged the source count rate.

We evaluated the optimal selection of source events by maximizing the source signal-to-noise ratio in the 0.15–10 keV range, as a function of:

- source extraction region. We considered different extraction radii in the 10$^{\circ}$–30$^{\circ}$ range; the background was extracted in any case from two rectangular regions located at the same distance from the readout node as the source region.

- threshold for high particle background screening. The observations are affected by a few short soft proton flares. We extracted a light curve in the 0.15–10 keV range with a 10 s time bin from the whole field of view for each camera. Following the prescription by (De Luca & Molendi 2004), we identified the quiescent average count rate and considered different thresholds in the 2–8 $\sigma$ range from such average rate.

The optimal choice turned out to be a source extraction radius of 18$^{\prime}$ for the pn and the MOS 1 camera and of 15$^{\prime}$ for the MOS 2 camera (which has a higher low-energy background), and a threshold at 5 $\sigma$ from the quiescent rate to screen from high particle background episodes. The resulting source and background counts statistics are shown in Table 1.

3. TIMING ANALYSIS

3.1. Pulsations from PSR J0737–3039A

For the search of pulsations at the spin period of pulsar A we could only use the pn data (~4,700 counts), owing to the inadequate time resolution of the MOS data. The times of arrival were converted to the Solar system barycenter and corrected for the orbital motion and relativistic effects of the binary system according to (Blandford & Teukolsky 1976). This was done with a program we wrote ad hoc and tested using an XMM-Newton observation of the binary millisecond pulsar XTE J1751–305 (Miller et al. 2003). As a further cross-check, we also compared the rotational phases obtained by our program with those resulting from the TEMPO timing analysis software [http://www.atnf.csiro.au/research/pulsar/tempo]. The maximum discrepancy between timing corrections from our program and TEMPO is at most of a few microseconds.

In our search for pulsations we employed the $Z_{\text{n}}^2$ test (Buccheri et al. 1983), where we indicate with $n$ the number of harmonics. We examined a wide frequency range centered on the value predicted at the epoch (MJD 54034) of our XMM-Newton observation by the radio measurements of Kramer et al. (2006). The most significant $Z_{\text{n}}^2$ statistics occurred for $n = 1$ at $P_{\text{best}}^\text{radio} = 22.6993787(5)$ ms ($1 \sigma$ errors in the last digit are quoted in parenthesis). The corresponding $Z_{\text{n}}^2$ value is 378.91, which, even taking into account the ~10$^4$ searched periods, has a virtually null probability of chance occurrence. Our best fit period is consistent with the value $P_{\text{radio}}^\text{A} = 22.699378466112(5)$ ms expected from the radio ephemeris of Kramer et al. (2006).

The background-subtracted and exposure-corrected light curve of pulsar A in the 0.15–4 keV energy range is
shown in the top panel of Fig. 1 (due to the soft pulsar spectrum the signal to noise ratio above 4 keV is very small). Error bars are calculated according to the expression \( \sigma_i = \sqrt{C_i + B_i \times f_i^2 / E_i} \), where \( C_i \), \( B_i \) and \( E_i \) are respectively the total counts, background counts and exposure in the bin \( i \), and \( f \) is the ratio between source and background extraction area (\( f \approx 0.11 \)). We checked that the pulsations are significantly detected down to the lowest energy bins covered by the pn instrument: in fact, the Pearson statistics for a 10 bins light curve in the 0.15–0.2 keV range gives a reduced \( \chi^2 \) (hereafter \( \chi^2_r \)) of 3.85, corresponding to a 4\( \sigma \) detection.

The pulse profile is double peaked and deeply modulated, with a pulsed fraction of \((75.7 \pm 5.4)\%\) in the energy range 0.15–4 keV. To calculate the pulsed flux, we considered all the counts above the minimum of the light curve, using the expression \( P F = C_{\text{tot}} - n \times N_{\text{min}} \) and its associated error \( \sigma_{PF} = \sqrt{C_{\text{tot}} + n^2 \times \sigma_{N_{\text{min}}}^2} \approx n \sqrt{N_{\text{min}}} \), where \( C_{\text{tot}} \) are the total counts, \( n \) the is number of bins in the light curve and \( N_{\text{min}} \) are the counts of the minimum. The expression \( (C_{\text{max}} - C_{\text{min}}) / (C_{\text{max}} + C_{\text{min}}) \) used by Chatterjee et al. (2007) does not account for the pulsed flux associated to secondary peaks, nevertheless their pulsed fraction value is in agreement with our result within 1\( \sigma \). Both methods are "bin dependent", but reasonable different choices of the number of bins (i.e. \( n > 10 \)) do not significantly affect the results. Note that the pulsed fraction upper limit of 60\% obtained in the short 2004 XMM-Newton observation referred to a sinusoidal profile (Pellizzoni et al. 2004), and therefore it is not inconsistent with the present result.

A simple hardness ratio analysis, based on the soft (\( S \); 0.15–0.3 keV) and hard (\( H \); 0.8–3 keV) energy ranges\(^5\), indicates a softer spectrum in correspondence of the minimum in the folded light curve (see bottom panel of Fig. 1). To investigate the energy dependence of the pulsed fraction in more detail, and as a cross-check of complementary phase-resolved spectral studies discussed below, we produced the folded light curves for four different energy ranges (0.15–0.3 keV, 0.3–0.5 keV, 0.5–0.8 keV, 0.8–3 keV) providing 800–900 source counts each (Fig. 2). The corresponding pulsed fractions, plotted in Fig. 3 increase from 50\% to 90\% from lower to higher energies. These values have a probability smaller than 1\% of deriving from an energy independent distribution.

We searched for possible flux and pulse profile variations due to the pulsars mutual interaction as a function of the orbital phase. For example, if there is a bow-shock structure as that described in Lyutikov (2005), associated to an unpulsed variable component (see Section 5), we would expect variations in the total flux correlated with changes in the pulsed fraction. In Fig. 4 (top) we

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\(^5\) The hardness ratio is defined as \((H - S) / (H + S)\), where for each phase bin \( H \) and \( S \) are the background-subtracted count rates in the hard and soft ranges.

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### Table 1

| Orbit | Detector | Total counts\(^a\) | Background fraction\(^b\) | Exposure time\(^c\) (ks) |
|-------|----------|-------------------|--------------------------|--------------------------|
| 1260  | pn       | 2,483             | 24.5%                    | 80.7                     |
| 1260  | MOS1     | 652               | 21.7%                    | 111.5                    |
| 1260  | MOS2     | 750               | 26.1%                    | 112.3                    |
| 1261  | pn       | 2,222             | 23.6%                    | 74.9                     |
| 1261  | MOS1     | 587               | 19.7%                    | 102.9                    |
| 1261  | MOS2     | 697               | 20.5%                    | 103.9                    |

\(^a\) Total number of counts inside the source extraction region.

\(^b\) Contribution of background to total number of counts.

\(^c\) Good observing time after dead-time correction and screening for soft-proton flares.
Fig. 2.— Background-subtracted light curves of PSR A for four energy intervals providing 800–900 counts each. The count-rate of the minimum of the light curve is compatible with 0 at high energies, while at low energies the presence of significant unpulsed flux is apparent.

Fig. 3.— Pulsed fraction of PSR A (crosses) as a function of energy (energy intervals as in Fig. 2). The plot shows also the predicted pulsed flux (triangles, stars, squares) for the spectral models discussed in Sections 4 and 5.

Report the pulsed fraction and total flux obtained from the folded 0.15–3 keV light curves integrated in four orbital phase intervals. The pulsed fraction varies in the 50–80% range with the minimum corresponding to the superior conjunction of A (when A is occulted by B; dotted line). However, the values are consistent at the 5.5% level with a uniform distribution and there is no corresponding change in the total flux. A similar analysis dividing the orbit in eight parts (Fig. 4, bottom) gave only a marginal evidence of a ~15% variability (null hypothesis probability n.h.p. = 1.5%) in the pn flux.

To calculate upper limits on orbital flux modulation, we considered the fraction of the counts above the minimum of the light curve with errors evaluation similar to those described in Section 3.1. For time-scales of ~15 min (10 bins) the 1σ u.l. on variability (pn+MOS data) is of 11.5% for the 0.15–4 keV range and <20–30% for the selected bands mentioned above. Longer time-scales of 0.5–1 hours imply upper limits <10% on all energy selections.

The search for orbital and aperiodic variability even selecting the time intervals corresponding to the minimum in the PSR A folded light curve does not improve the above upper limits.

3.2. Pulsations from PSR J0737–3039B

We searched for pulsations from PSR B using the same method and radio ephemeris reference as for PSR A [Kramer et al. 2006], but in this case, owing to the longer pulse period, we could also use the lower time resolution MOS data. The expected pulsar period at the epoch of our observation is \( P_{\text{radio}} = 2.7734607024(7) \) s, with an uncertainty orders of magnitude smaller than the intrinsic pulse search resolution of our data set, \( \frac{1}{2}P_{\text{B}}/T_{\text{OBS}} \approx 1.4 \times 10^{-5} \) s. Thus, if the rotational parameters of the neutron star are stable (as suggested by radio ephemeris) a single-trial pulse search at \( P_{\text{B}} \) is ap-
appropriate. However, since we cannot in principle exclude that (unlikely) glitches and/or significant timing noise occurred in the time between the radio and X-rays observations, we also performed a search in a range of periods around $P^{\text{radio}}_B$. In any case, no significant pulsations were detected in the whole energy range nor in our canonical bands (0.15–0.3 keV, 0.3–0.5 keV, 0.5–0.8 keV, 0.8–3 keV) providing 1200–1400 source counts each. The upper limit on the pulsed flux fraction is of 40%.

Since the radio flux of PSR B is strongly modulated as a function of the orbital phase and is nearly disappearing around superior conjunction of A (when A is occulted by B). (lower panel) bins. The dotted vertical line corresponds to the pulse search. We tried to better constrain the orbital phase interval corresponding to a positive detection of PSR B by shifting and/or shortening the orbital phase intervals of the period search. However we did not find more significant detections, and, considering the low statistics pulsed data, we cannot derive tighter constraints.

As mentioned above, the stability of the timing parameters of this neutron star is likely, but not guaranteed. Thus, in principle, a strict single-trial search at the predicted value $P^{\text{radio}}_B$ might not be the optimal strategy. Furthermore, a blind search in period is an important cross-check to claim a robust pulsed detection. We therefore searched also for other peaks in the $Z^2_\phi$ distributions around $P^{\text{radio}}_B$. We did not find more significant detections apart from values close (within the pulse search resolution) to $P^{\text{radio}}_B$ (Fig. 4). The best-fit pulse period is $P^\text{best}_B = 2.773459(4)$ s providing a probability of only $10^{-6}$ ($Z^2_\phi = 42.63, 4.9\sigma$) that we are sampling a uniform distribution.

The resulting pn light curves for the four phase intervals considered are shown in Fig. 6. The pulse profile appears highly structured and with a pulsed flux fraction of $35 \pm 15\%$ in the energy range 0.15–3 keV.

The detection of PSR B in MOS data is only marginal and the analysis of merged MOS and pn data does not provide better detection significance (even selecting counts which are in the lowest emission bins of the pulse profile of PSR A), probably because the 0.3 s time resolution of the MOS dilutes the sharp peaks of the light curve. Furthermore, the poor effective area of the MOS at low energies (i.e. negligible in the 0.15–0.3 keV band) is not efficient for pulse searches in sources with very soft spectra. In fact, although PSR B is also marginally detected at $E > 0.5$ keV ($\chi^2_\phi = 2.1, 19\d.o.f.$), most of flux contributions to the main peaks of its light curve comes from the low energy band.

In the hypothesis that PSR B is emitting X-rays only in the orbital phases in which we can firmly claim pulse de-
Fig. 6.— light curves of PSR B folded at period $P_{\text{best}} = 2.773459(4)$ s as a function of the orbital phase. The pulsar is detected at 4.9σ-level around the ascending node (orbital phase interval 0.41–0.66).

In contrast with the previous short Chandra and XMM-Newton observations (McLaughlin et al. 2004a; Pellizzoni et al. 2004; Campana et al. 2004), single component models fail to properly fit the data. A blackbody model is completely ruled out and only a very steep power law provides a barely acceptable fit (n.h.p. = 4%). Either a double blackbody or a power-law plus blackbody model are instead an adequate fit (n.h.p. > 50%). In the two-components models, the derived column density is also in better agreement with the value estimated from the radio pulsars’ dispersion measure ($N_H = 1.5 \times 10^{20}$ cm$^{-2}$, assuming 1 H for each electron; Campana et al. 2004). The power-law photon index in the PL+BB model is still very soft. A hard power-law with photon index $\Gamma \sim 2$, as expected for a shock emission, does not provide an acceptable fit. The observed flux in the 0.2–3 keV energy range is $4.0 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an unabsorbed luminosity $L_X = 2.2 \times 10^{30}d_{0.5}^2$ erg s$^{-1}$ for the PL+BB model. The radio dispersion measure distance of $\sim 500$ pc is based on a model for the interstellar electron density (Cordes & Lazio 2002) and the parallactic distance ranges from 0.2 to 1 kpc (Kramer et al. 2006) implying uncertainties of a factor $\sim 4$ in luminosity estimates.

The good timing resolution coupled to the simultaneous spectral capability of the pn data, together with the relatively large number of detected source photons, allowed us to perform for the first time a phase-resolved spectral analysis for PSR A. Three spectra were ex-
tracted selecting the pn events (with pattern equal to 0) in the three phase intervals shown in Fig. 1 corresponding to the off-pulse (phase A), the interpulse (phase B), and the main pulsation peak (phase C). The results of the fit of these three spectra with the four models used for the phase-averaged spectrum are shown in Table 3.

A single blackbody model does not provide an acceptable fit for any of the three spectra. We also note that, while the best-fit parameters of the main peak (phase C) and interpulse (phase B) are very similar to those of the phase-averaged spectrum, the fits of the off-pulse spectrum (phase A) with the two-components models converges to rather different values for some parameters. In particular, in the double blackbody model, one of the two blackbodies has a temperature \( \sim 10 \) times smaller (and a correspondingly larger emitting area) than in the other two phase intervals. Moreover, in the PL+BB model the power-law component is steeper and, in both cases, the column density is significantly larger.

To better check if the source spectrum is actually changing with the phase of PSR A, we simultaneously fitted the three phase-resolved spectra with the same blackbody plus power-law model with all the parameters linked together, except for an overall normalization factor. A globally acceptable fit is obtained, but if we compute separately the \( \chi^2 \) for each, fixing all the parameters to the best-fit values of the simultaneous fit, we note that the fit of the off-pulse spectrum is unacceptable (see Table 3). The corresponding residuals (see Fig. 7) show a soft excess in the off-pulse spectrum, confirming the softening in the pulse minimum already displayed in the phase-averaged spectrum. Since a good fit of the off-pulse spectrum is also obtained using a PL+BB model (see Table 3), we also tested a model where the unpulsed spectrum was composed by a power-law plus blackbody spectrum with linked parameters, except for an overall normalization factor (see Table 3). For the spectrum of the pulse peak (in black), the relative contribution of the power-law (blue) and blackbody (light blue) components are also shown in the spectrum. The residuals are shown separately for each spectrum in standard deviation units.

We tested also the possibility that separate physical processes, producing different spectral components, were responsible for the pulsed and unpulsed emission. A first hypothesis, already proposed by Chatterjee et al. (2007), where a blackbody accounts for the unpulsed emission and a power-law for the pulsation is immediately discarded by the fact that the off-pulse spectrum cannot be well fitted by a single blackbody model (see Table 3).

The off-pulse spectrum is instead well fitted by two blackbodies. Therefore we tried to fit the phase-resolved spectra with a three-component model composed of two constant blackbodies and a power-law with stable photon index and variable normalization. The resulting fit is very good and its parameters are shown in Table 4.

Since a good fit of the off-pulse spectrum is also obtained using a PL+BB model (see Table 3), we also tested a model where the unpulsed spectrum was composed by a blackbody plus a power-law and a second blackbody was responsible for the pulsed emission. In this model, the two blackbodies might come from the surface of the two pulsars and the power-law from a shock. However, the resulting fit, also reported in Table 4, is not acceptable.

### Table 2

Summary of the spectral results in the 0.15–10 keV energy range. Errors are given at the 90% confidence level and are not reported for the single blackbody model because the fit is largely unacceptable.

| Instrument | Model   | \( N_H \) \( (10^{20} \text{cm}^{-2}) \) | \( \Gamma \) | PL norm. | \( k_B T_{BB_H} \) \( (\text{eV}) \) | \( R_{BB_H} \) \( (\text{m}) \) | \( k_B T_{BB_C} \) \( (\text{eV}) \) | \( R_{BB_C} \) \( (\text{km}) \) | \( \chi^2 \) (d.o.f.) |
|------------|---------|---------------------------------|--------|------------|----------------|----------------|----------------|----------------|----------------|
| pn         | PL      | \( 4.6^{+0.8}_{-0.7} \)         | 3.4 ± 0.1 | 9.4 ± 0.6 | ...            | ...            | ...            | ...            | 1.38 (50)     |
|            | BB      | ...                             | ...     | ...        | ...            | ...            | ...            | ...            | ...            |
|            | BB+BB   | < 0.9                           | ...     | ...        | ...            | ...            | ...            | ...            | 3.29 (50)     |
| pn+MOS     | PL      | \( 3.2^{+1.3}_{-1.4} \)         | 3.3 ± 0.3 | 6.6 ± 1.3 | 280 ± 40       | 23 ± 12         | 110 ± 8        | 0.23 ± 0.05   | 1.14 (48)     |
|            | BB      | ...                             | ...     | ...        | ...            | ...            | ...            | ...            | ...            |
|            | BB+BB   | < 0.5                           | ...     | ...        | ...            | ...            | ...            | ...            | 3.05 (98)     |
|            | PL+BB   | 3.0 ± 1.1                       | 3.2 ± 0.1 | 6.5 ± 1.0 | 150 ± 20       | 80 ± 30         | ...            | ...            | 0.92 (96)     |

\( ^a \) In units of \( 10^{-6} \) ph. cm\(^{-2} \) s\(^{-1} \) keV\(^{-1} \), at 1 keV.

\( ^b \) Assuming a distance of 500 pc.
TABLE 3

Results of the phase-resolved spectroscopy performed with the pn single events in the 0.15–10 keV energy range. Errors are given at the 90% confidence level and are not reported for the single blackbody model because the fit is largely unacceptable.

| Model | Phase interval | \(N_H\) (10^{20} cm\(^{-2}\)) | \(\Gamma\) | PL norm,a | \(k_B T_{BBH}\) (eV) | \(R_{BBH}\) b (m) | \(k_B T_{BBC}\) (eV) | \(R_{BBC}\) b (km) | \(\chi^2_{\nu}\) (d.o.f.) |
|-------|----------------|-------------------|-------|----------|-----------------|------------|-----------------|------------|-----------------|
| PL    | A              | 2.1^{+2.2}_{-1.0} | 3.5^{+0.5}_{-0.3} | 2.9^{+0.7}_{-0.6} | ... | ... | ... | ... | 1.37 (9) |
|       | B              | 4.9^{+1.6}_{-1.4} | 3.3^{+0.3}_{-0.2} | 8.6^{+1.0}_{-0.9} | ... | ... | ... | ... | 0.99 (23) |
|       | C              | 5.0^{+1.2}_{-1.1} | 3.4^{+0.2}_{-0.2} | 13.4^{+1.5}_{-0.9} | ... | ... | ... | ... | 1.11 (42) |
| BB    | A              | 0.1                   | ... | ... | 118 | 149 | ... | ... | 2.57 (9) |
|       | B              | 0                     | ... | ... | 141 | 138 | ... | ... | 2.16 (23) |
|       | C              | 0                     | ... | ... | 146 | 167 | ... | ... | 2.67 (42) |
| BBH+BBC | A           | 9.0^{+3.2}_{-3.0}    | ... | ... | 140^{+20}_{-10} 130^{+40}_{-40} | 29^{+22}_{-14} 35.8^{+33.3}_{-35.4} | 0.94 (7) |
|       | B              | < 1.9                 | ... | ... | 370^{+150}_{-70} 11^{+15}_{-15} 120^{+70}_{-70} | 0.18^{+0.06}_{-0.02} | 0.86 (21) |
|       | C              | < 2.3                 | ... | ... | 260^{+50}_{-50} 34^{+24}_{-24} 100^{+50}_{-50} | 0.30^{+0.06}_{-0.06} | 1.00 (40) |
| PL+BB | A              | 10^{+3}_{-2.9}        | 9.9^{+6.3}_{-6.7} | 0.02^{+0.70}_{-0.01} | 140^{+20}_{-20} 120^{+40}_{-40} | ... | ... | 1.14 (7) |
|       | B              | 2.0^{+4.8}_{-2.8}    | 2.7^{+0.7}_{-0.7} | 5.3^{+2.8}_{-2.6} | 120^{+30}_{-30} | 0.14^{+0.09}_{-0.09} | ... | ... | 0.88 (21) |
|       | C              | 4.0^{+1.7}_{-1.0}    | 3.5^{+0.6}_{-0.3} | 9.7^{+4.2}_{-4.2} | 190^{+50}_{-50} | 50^{+30}_{-30} | ... | ... | 0.95 (40) |

\(^a\) In units of 10^{-6} ph. cm^{-2} s^{-1} keV^{-1}, at 1 keV.
\(^b\) Assuming a distance of 500 pc.

TABLE 4

Results of simultaneous fit of the three phase-resolved pn spectra of PSR A. Errors are given at the 90% c. l.

| Fixed component | Variable component | Phase interval | \(N_H\) (10^{20} cm\(^{-2}\)) | \(\Gamma\) | PL norm,a | \(k_B T_{BBH}\) (eV) | \(R_{BBH}\) b (m) | \(k_B T_{BBC}\) (eV) | \(R_{BBC}\) b (km) | \(\chi^2_{r,single}\) (d.o.f.) | \(\chi^2_{r,tot}\) (d.o.f.) |
|----------------|-------------------|----------------|-------------------|-------|----------|-----------------|------------|-----------------|------------|-----------------|-----------------|
| ...            | PL+BBc            | A              | 3.2^{+1.4}_{-1.3} | 3.2^{+0.2}_{-0.3} | 3.0^{+0.9}_{-1.8} | 150^{+50}_{-50} | 45^{+30}_{-20} | ... | 2.15 (12) |
|                |                   | B              | 9.5^{+3.6}_{-1.9} | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |...
ing pulsed flux (~50%) as shown by the stars plotted in Fig. 3. A similar argument applies for the case of the double blackbody model (see triangles plotted in Fig. 3). These results are confirmed by the phase-resolved spectra of PSR A showing that the off-pulse spectrum cannot be well fitted by a single component model.

More in general, none of the double component best-fit models is compatible with the plot in Fig. 3 even in the assumption that the pulsed flux results from a combination of both spectral components. In fact, the total flux of the softer spectral component (either the power-law or the colder blackbody) is 3–4 times higher than that of the harder component. Therefore, it is impossible to invert the trend in Fig. 3 even assuming that the harder component is fully pulsed. For example, in the case of the PL+BB model, assuming that the pulsed flux is due to the full blackbody component plus a part of the power-law component, it is impossible to obtain a pulsed fraction increasing with energy. Therefore, the entire X-ray flux of the double pulsar system cannot be interpreted as a simple combination of a non-thermal and single-temperature thermal emission from PSR A or PSRB. Therefore, on the basis of these considerations and of the spectral results of Section 4, we are led to consider models based on three spectral components.

The inclusion of an additional cooler blackbody BBc (possibly related to PSR B) in the PL+BB model can account for the small pulsed fraction at low energy. Three-component models where blackbody emission (BBH) is responsible of most of the pulsed emission from PSR A do not provide an acceptable spectral fit (see Table 4) and fail to match pulsed flux fractions in Fig. 3. Assuming instead that most of the pulsed PSR A flux is due to the power-law, it is possible to reproduce the trend seen in Fig. 3 (squares). This is also the best three-component scenario compatible with the phase-resolved spectrum of PSR A (see Section 4, Table 4). It is worth noting that the phase-resolved spectrum of PSR A does not reveal any variation apart from a significant softening in the off-pulse phases, in agreement with the proposed three-component model.

The best three-component model fitting phase-resolved spectrum of PSR A and pulsed fluxes of both pulsars is thus composed of a power-law with photon index $\Gamma \sim 3.3$ and 0.2–3 keV luminosity $L_{PL} = 1.9 \times 10^{30}$ erg s$^{-1}$, a cooler ($\sim 30$ eV) blackbody with bolometric luminosity $L_{BBc} = 3.0 \times 10^{31}$ erg s$^{-1}$, and a hotter blackbody ($\sim 130$ eV) with luminosity $L_{BBH} = 5.2 \times 10^{29}$ erg s$^{-1}$. The emission from PSR A is mostly non-thermal, being its luminosity equal to $L_{PL}$ plus the possible additional smaller contribution of $L_{BBH}$; $L_A \sim 2 \times 10^{30} = 3 \times 10^{-4} \dot{E}_A$ in the 0.2–3 keV energy range.

Due to the softness of the spectrum, the efficiency of the conversion of rotational energy loss into X-ray luminosity is strongly sensitive to the energy range considered. The PSRA luminosity in the 0.1–10 keV range is matching $\sim 10^{-3} \dot{E}_A$, the value typically found for recycled radio pulsars that are detected at X-ray energies (Becker & Trumper 1999). As expected from a mostly magnetospheric emission, pulse peaks are still relatively steep and far from thermal broad sinusoidal pulsations seen in other recycled pulsars with comparable spin parameters (Zavlin et al. 2002). Non-thermal deeply modulated components are instead seen in the pulsed flux of the most energetic recycled pulsars (e.g. PSR B1821–24). The peculiar nature of PSRA is also stressed by the fact that no other recycled pulsar with such a steep non-thermal emission component is known.

The observed equivalent emitting radius of BBH is one order of magnitude smaller than the polar cap radius of PSRA ($\sim 1$ km), but modeling with a non-uniform temperature of the heated region (Zavlin et al. 2002) or invoking a partially filled polar cap (Harding & Muslimov 2002) could solve this discrepancy. Thus we can interpret BBH as due to the heating of A’s polar cap from back-flowing particles in its magnetosphere. The light curve of PSRA shows a bridge between the two peaks 2–3 times higher than the off-pulse flux, leading to the idea that both non-thermal pulses emerge from a wide, center-filled thermal emission cone from the magnetic pole possibly associated to BBH.

5.1. The nature of PSR B X-ray emission

We detected PSRB during part of the orbit, around the ascending node. Its 0.2–3 keV flux estimated from the pulsed light curve is $\sim 1.2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and corresponds to $(35 \pm 15\%)$ of the total flux in the orbital phase interval 0.44–0.61. The corresponding luminosity of $3.6 \times 10^{29}$ erg s$^{-1}$, represents $\sim 20\%$ of the spin-down energy loss, a value much higher than observed in all the other normal pulsars (Possenti et al. 2002).

The PSRB emission is likely associated to the cooler blackbody emission BBc ($k_B T \approx 30$ eV), with the possible addition of the weaker and hotter component BBH (if the latter is not associated to PSRA). In this case, the bolometric luminosity of PSRB can be calculated as $L_B \approx 4 \times L_{BBc} \approx 1.2 \times 10^{32}$ erg s$^{-1}$ assuming it is emitted during one-fourth of the orbit ($L_{BBc}$ and $L_{BBH}$ are orbital phase-averaged luminosities). This luminosity is surprisingly much higher than the X-ray emission from PSRA (assuming $L_A \approx L_{PL} = 1.9 \times 10^{30}$ erg s$^{-1}$). Obviously, X-ray emission from PSRB can be only powered by an external source, i.e. the spin-down energy from PSRA. In this hypothesis, $\sim 2\%$ of the rotational energy loss of PSRA is converted in thermal radiation from PSRB.

Zhang & Loeb (2004) explain the strong brightening of pulsed radio flux from PSRB in two portions of the orbit as episodes during which pairs from pulsar A’s wind flow into the open field line region of pulsar B and emit curvature radiation at radio frequencies within an altitude of $\sim 10^8$ cm. Once pairs from A’s wind leak into B’s magnetosphere, they will stream all the way down, heating the surface of B, giving rise to thermal radiation. According to this model the predicted X-ray luminosity is

$$L_{X,B} \sim 2 \times 10^{31} \eta (\Delta \Omega_{w,A}/4\pi)^{-1} \text{erg s}^{-1}$$

and the typical temperature of the polar cap of PSRB is

$$k_B T_{pc} \approx 0.4 \eta^{1/4} (\Delta \Omega_{w,A}/4\pi)^{-1/4} \text{keV}$$

where $\eta$ is the fraction of all pairs from A’s bow shock injected into B’s open field line region and $\Delta \Omega_{w,A}$ is the unknown solid angle of A’s wind.

The X-ray luminosity predicted by the model is in good agreement with our results if we assume that PSR A’s wind is anisotropic (i.e. $\Delta \Omega_{w,A} \lesssim 1$ sr), as heuristically
suggested by the variable illumination inducing radio and X-rays emission of PSR B. Within the above anisotropy assumption, the required efficiency \( \eta \) is (poorly) constrained to \( \lesssim 50\% \) to match the observed PSR B luminosity.

However, according to this model, the PSR B’s surface would be heated to a temperature (\( \sim 500 \text{eV} \)) higher than the observed values of \( \text{BB}_C \) and \( \text{BB}_H \). This discrepancy could be due to the fact that most of the predicted luminosity (\( \text{BB}_C \)) comes from a region larger than the polar cap and consistent with the whole neutron star’s surface. The hotter component is consistent in size with the polar cap and could be responsible for the observed pulsations.

In radio, the shape and the intensity of the pulse profile of PSR B vary with orbital longitude, with two bright phases centered around longitudes (with respect to the ascending node) of \( \sim 210^\circ \) (bp1, orbital phase 0.11) and \( 280^\circ \) (bp2; orbital phase 0.31) at the epoch of first observations \( [\text{Lyne et al. 2004}] \). Due to geodetic precession of pulsars’ spins and periastron advance, these bright phases are shifting to greater longitudes at a rate of few degrees yr\(^{-1} \) \( [\text{Burigav et al. 2005}] \). At the epoch of our \( \text{XMM-Newton} \) observation, the centroid of the radio bright phase bp1 is expected at \( \sim 300^\circ \) of longitude (orbital phase 0.36). The brightening of PSR B in X-rays appears in the orbital phase interval adjacent (following) to bp2 and peaks around the ascending node. When PSR A’s wind intercepts PSR B’s magnetosphere it powers radio emission and it starts heating B’s surface. The X-ray emission from B lasts for \( (30 \pm 10) \) min each orbit (detection significance fades outside this range) constraining the thermal inertial time of the neutron star in good agreement with theoretical expectations for external heating of a pulsar surface \( [\text{Eichler & Cheng, 1989}] \).

5.2. Constraints on X-ray emission from a bow-shock between A’s wind and B’s magnetosphere

The short occultation of A by B seen in the radio band \( [\text{Lyne et al. 2004}] , \text{McLaughlin et al. 2004}] \) could imply the presence of a dense magnetosheath enfolding the magnetosphere of PSR B, although all the absorption could occur form within the B’s magnetosphere alone \( [\text{Lyutikov & Thompson, 2003}] \). In the magnetosheath model, the relativistic wind from A collides with B’s magnetic field at an equilibrium distance from B comparable or smaller than the radius of its light cylinder \( [\text{Arons et al. 2003}, \text{Lyutikov, 2004}] \). Thus, in contrast with termination shocks seen in pulsar wind nebulae (PWNe) typically at distances \( >10^8 \) light cylinder radii, a termination shock between PSR A and PSR B could probe the properties of a pulsar’s relativistic wind at a smaller distance from the central engine than ever studied before. PWNe are usually strongly radiative at high energies with typical efficiencies \( L_X/E_{\text{PSR}} = 10^{-2} - 10^{-3} \). Therefore, some trace of a peculiar PWN originating by PSR B’s magnetic pressure confining the wind outflow from A should be in principle found as a non-thermal component in our data.

An important issue concerning such a bow-shock/magnetosheath model is that one might expect a flux modulation as a function of the orbital phase owing to the changing view of the shock front. In particular, the shocked wind is expected to flow away from the head of the bow-shock in a direction roughly parallel to the shock \( [\text{Lyutikov, 2004} , \text{Granot & Mészáros, 2004}] \). This might imply relativistic beaming of the radiation emitted by the shocked plasma, resulting in a \( \lesssim 50\% \) modulation of the observed emission as a function of the orbital phase with possible peaks at 90° from conjunctions.

The upper limits we obtained on the flux variations as a function of the orbital phase allow us to exclude any significant orbital modulation \( > 15\% \) in X-rays (Section 3.1). Assuming that most of the unpulsed flux of the system (\( \sim 10-50\% \) of the total flux depending on the selected energy range) could be ascribed to the bow-shock, flux variations should have been detected. In fact, the range of allowed spectral slopes of non-thermal components in our spectral fits is not compatible with the “canonical” shock value \( \sim 2, \) although a soft post-shock spectrum could be explained with the presence of an unusual low-energy relativistic electron population, as required in the magnetosheath model to provide A and B’s eclipses by synchrotron absorption \( [\text{Arons et al. 2003}, \text{Lyutikov, 2004}] \). Nevertheless, the off-pulse spectrum of PSR A is not even compatible with a simple non-thermal emission and PSR B would fill most of it at least for the part of the orbit in which it is detected. Therefore there is not much room left for a shock emission component in our data. An upper limit (90% c.l.) \( \lesssim 10^{39} \text{erg s}^{-1} \) \((0.2-3 \text{keV})\) corresponding to an efficiency of \( L_X^{\text{shock}}/E_A = 2 \times 10^{-5} \) can be obtained by evaluating the maximum allowed luminosity of an unpulsed power law component with photon index \( \sim 2 \) in the off-pulse spectrum of PSR A.

Such a low output in shock emission compared to typical PWNe’s \( L_X^{\text{shock}}/E_{\text{PSR}} \) is not surprising looking at the small solid angle over which the wind from A is intercepted by B and considering that the termination shock of the wind is much closer than in known nebulae and then it could show a different phenomenology.

Assuming that the wind energy is radiated isotropically from PSR A, and that it is intercepted by a sphere centered on PSR B with radius equal to its light cylinder \( R_{\text{lc,B}} \), the resulting shock emission efficiency is \( L_X^{\text{shock}}/E_{\text{PSR}} = k \times R_{\text{lc,B}}/d^2 \times f(\sigma_M) \), where \( d \) is PSRs separation, \( f(\sigma_M) \) is the fraction of power intercepted by the shock feeding into the accelerated electrons (it is a function of the unknown magnetization parameter \( \sigma_M \)), and \( k \) is a normalization factor to fit observed “standard” PWNe X-ray efficiencies, where \( \sigma_M \ll 1 \).

Kennel & Coroniti \( [\text{1984}] \) provide an extensive discussion of shock power function \( f(\sigma_M) \) that is proportional to \( 1/\sqrt{\sigma_M} \) for \( \sigma_M \gg 1 \) (high-\( \sigma_M \) shocks have poor efficiency) and is \( \lesssim 1 \) for \( \sigma_M \ll 1 \). Fig. 5 shows the resulting \( L_X^{\text{shock}}/E_{\text{PSR}} \) curve as a function of the magnetization parameter \( \sigma_M \) accounting for uncertainties (filled band) associated to the actual size of the region intercepting the shock (it could be a factor 5 smaller than \( R_{\text{lc,B}} \) according to pressure balance) and errors on \( k \) due to the observed span in PWNe efficiencies. For low values of the magnetization parameter, the shock could theoretically account for a significant fraction of the X-ray luminosity, but this is not the case: the observed upper limit (dotted-dashed line) constrains the magnetization parameter to values \( \gtrsim 1 \) and thus much higher than those estimated for Crab-like PWNe. Such an high magnetization parameter is apparently inconsistent with the value of \( \sim 0.03 \) pre-
dicted by the magnetosheath model (Arons et al. 2005) and it seems to confirm most of modern wind models (Contopoulos & Kazanas 2002; Lyubarsky & Kirk 2001) predicting $\sigma_M \gg 1$.

Granot & Mészáros (2004) proposed a model in which the emission from the interaction of the two pulsars is lower than that expected from the interaction of pulsar A’s wind alone with the interstellar medium (ISM). Thus, PSR A could provide a “standard” PWN ($\sigma_M \ll 1$) at distances of $\sim 10^{15}$ cm from the pulsar surface. In this model, little or no modulation with the orbital period, $P_A$, and $P_B$ is expected, but even in this case it is difficult to account for the steepness of the unpulsed spectrum. Furthermore, the predicted luminosity of this model in the energy range (0.2–10 keV) is $\sim 7 \times 10^{30}$ erg s$^{-1}$, much higher than our upper limit on the shock component discussed above.

6. CONCLUSIONS

The analysis of the $\sim 5,600$ source photons obtained from our $\sim 230$ ks long $\textit{XMM-Newton}$ observation confirmed the pulsed detection in X-ray of PSR A providing 80% of the total absorbed flux from the system. For the first time, X-ray emission from PSR B is also detected with good confidence ($\sim 200–300$ pulsed counts) around the ascending node of the orbit.

A three-component spectral model can satisfactorily fit phase-resolved spectra and the energy dependence of the PSR A pulsed fraction. The best-fit model is composed of a soft power-law responsible of most of the pulsed emission from PSR A (accounting for only $\sim 15\%$ of the total unabsorbed luminosity at $E > 0.1$ keV), a cooler ($\sim 30$ eV) blackbody likely associated to PSR B, and a hotter and fainter thermal component originating from back-falling particles heating polar caps of either PSR A or PSR B ($R_{\text{BHH}} \sim 100$ m). Note that the cooler blackbody accounts for most of the bolometric luminosity, even if its contribution in the $\textit{XMM-Newton}$ energy range is small.

PSR A shows peculiar properties with respect to other known recycled pulsars (e.g. the softest non-thermal spectrum) possibly due to the particular evolutionary history of a double neutron star system. The phenomenology of PSR B is completely different from that of any other pulsar and the only viable possibility to explain its X-ray emission seems that it is powered by PSR A’s wind heating B’s surface. Our observation is in good agreement with theoretical predictions by models also explaining B’s radio flares (Zhang & Loeb 2004), although a more complex thermal emission scenario (colder and non-uniform temperature) should be invoked.

There are no signs (e.g. orbital flux modulation, a significant non-thermal component in the PSR A’s off-pulse) of the presence of X-ray emission from a bow-shock between A’s wind and B’s magnetosphere (Lyutikov 2004; Arons et al. 2003) invoked to explain the occultation of radio emission of PSR A at inferior conjunction of PSR B. The upper limit on the flux of such a shock component constrains the wind magnetization parameter $\sigma_M$ of PSR A to values $> 1$, much higher than that predicted by the magnetosheath radio occultation of PSR A. The absorption causing A’s occultation is likely to occur within the B’s magnetosphere which retains enough plasma to produce an eclipse (Lyutikov & Thompson 2003).

Further X-ray observations of PSR J0737–3039 with $\textit{XMM-Newton}$ and $\textit{Chandra}$ with reasonable exposure times ($< 1$ Ms) would not significantly improve PSR B detection and better constrain pulsars spectra. At gamma-ray energies the absence of the strong thermal components seen in X-ray could instead allow to reveal non-thermal emission from PSRs interactions and better constrain the magnetospheric emission from PSR A. The empirical relation between gamma-ray luminosity $L_\gamma$ and $\dot{E}$ for known gamma-ray pulsars (i.e. $L_\gamma \propto \sqrt{\dot{E}}$, Thompson 2004; Zhang & Harding 2000) yields $L_\gamma, \dot{E} \sim 10^{33}$ erg s$^{-1}$, a value compatible with the luminosity of the possibly related EGRET source 3EG J0747–3412 (Hartman et al. 1999) assuming the same distance. The gamma-ray pulsed emission of PSR A could be detected by the AGILE (Tavani et al. 2006) and GLAST (see http://glast.gsfc.nasa.gov/) missions.

Apart from PSR J0737–3039, the only other known X-ray emitting double neutron star binary (DNSB) is PSR J1537+1155 (Kargaltsev et al. 2006). The X-ray spectra of PSR J1537+1155 and PSR J0737–3039 are similar, and their X-ray luminosities are about the same fraction of the respective spin-down energies. We note that, if also the other DNSBs have a similar efficiency, no other known object of this class can be detected by the currently available X-ray telescopes. Unlike PSR J0737–3039, in PSR J1537+1155 the distribution of photon arrival times over binary orbital phase shows a deficit of X-ray emission around apastron, supporting the idea that most of the emission is caused by interaction of the relativistic wind from the pulsar with its neutron star companion. The difference between the two DNSBs can be explained by the smaller eccentricity of PSR J0737–3039 or different alignments between the equatorial plane of the millisecond pulsar and the orbital plane of the binary (Kargaltsev et al. 2006). Despite PSR J1537+1155 is weaker than PSR J0737–3039, it may offer better diagnostics to discriminate emission produced by the shocked wind from “standard” pulsar magnetospheric and surface emission and thus it is one of the most interesting systems suitable for further X-ray
investigations of the inner pulsar magnetospheres and wind parameters in compact systems.

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