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Simultaneous X-ray & radio observations of the radio-mode-switching pulsar PSR B1822–09

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ABSTRACT
We report on simultaneous X-ray and radio observations of the radio-mode-switching pulsar PSR B1822–09 with ESA’s XMM-Newton and the WSRT, GMRT and Lovell radio telescopes. PSR B1822–09 switches between a radio-bright and radio-quiet mode, and we discovered a relationship between the durations of its modes and a known underlying radio-modulation timescale within the modes. We discovered X-ray (energies 0.2–1.4 keV) pulsations with a broad sinusoidal pulse, slightly lagging the radio main pulse in phase by 0.094 ± 0.017, with an energy-dependent pulsed fraction varying from ~0.15 at 0.3 keV to ~0.6 at 1 keV. No evidence is found for simultaneous X-ray and radio mode switching. The total X-ray spectrum consists of a cool component (T ∼ 0.96 × 10^6 K, hot-spot radius R ∼ 2.0 km) and a hot component (T ∼ 2.2 × 10^8 K, R ∼ 100 m). The hot component can be ascribed to the pulsed emission and the cool component to the unpulsed emission. The high-energy characteristics of PSR B1822–09 resemble those of middle-aged pulsars such as PSR B0656+14, PSR B1055–52 and Geminga, including an indication for pulsed high-energy gamma-ray emission in Fermi LAT data. Explanations for the high pulsed fraction seem to require different temperatures at the two poles of this orthogonal rotator, or magnetic anisotropic beaming effects in its strong magnetic field. In the X-ray sky map we found a harder source at only (5.1 ± 0.5)′′ from PSR B1822–09, which might be a pulsar wind nebula.

Key words: stars: neutron — pulsars: general — Radio continuum: individual: PSR B1822–09 — X-rays: individual: PSR B1822–09

1 INTRODUCTION
In this paper we present the results of simultaneous X-ray and radio observations of the radio-mode-switching pulsar PSR B1822–09.

The project was stimulated by the success of an earlier similar campaign involving the mode-switching pulsar PSR B0943+10, which resulted in the discovery of synchronous mode switching in the pulsar’s radio and X-ray emission properties (Hermsen et al. 2013). This was then followed up by a more extended campaign (Mereghetti et al. 2016) in which the synchronous mode switching of PSR B0943+10 was confirmed and which enabled its nature to be better established, discovering that both pulsed and unpulsed X-ray emission are present in both modes but at differing levels and that these properties may evolve during one of the modes.

These completely unexpected results are of great importance for the understanding of the physical processes in pulsar magnetospheres. In addition, separate investigations have challenged the earlier perception that radio mode-switching is a detail of polar cap and/or magnetospheric physics by the identification of a relationship between the spin properties of neutron stars and their radio emission modes (Kramer et al. 2006; Lyne et al. 2010; Camilo et al. 2012; Lorimer et. al. 2012). The implication of these results is that mode switching is due to an inherent, perhaps universal, pulsar process which causes a sudden change in the rate of angular momentum loss that is communicated along the open field lines of the magnetosphere. This link with the rapid switching observed in radio emission modes suggests a transformation of the global magnetospheric state in less than a rotation period. Nevertheless, the two X-ray radio campaigns on PSR B0943+10 have yet to conclusively...
answer the fundamental question as to whether the discovered X-ray mode switching supports a local or global magnetospheric interpretation.

To build on the PSR B0943+10 discoveries we therefore searched radio and X-ray catalogues for an attractive alternative radio pulsar known to exhibit mode switching with mode occurrence fractions between ~30% and 70% (to enable statistically valid X-ray photon counts in both modes) and also reported to be an X-ray source. We did not find a suitable candidate there, but, searching the X-ray archives, we found that PSR B1822−09 had been in the XMM-Newton field-of-view in a short observation, in which we detected the X-ray counterpart. This pulsar has a younger characteristic age of 233 kyr and a shorter spin period $P_0 = 0.769$ s (compared with 5 Myr and 1.1 s for PSR B0943+10). It has many properties in common with PSR B0943+10, but also peculiarly different characteristics. Like PSR B0943+10, PSR B1822−09 also switches between a bright ‘B’ mode and a quiet ‘Q’ mode in its radio main pulse (MP), but on shorter times scales averaging a few minutes (compared with several hours for PSR B0943+10). Most remarkably, its Q-mode exhibits an interpulse (IP), located at about half a rotation period from the MP, which switches mode in anticorrelation with the MP (Fowler, Morris & Wright 1981; Fowler & Wright 1982; Gil et al. 1994). The B mode, in contrast to PSR B0943+10, exhibits a brighter but more complex MP as well as a precursor component (PC) some 15° longitude prior to the MP, but a barely detectable IP.

Both PSR B0943+10 and PSR B1822−09 exhibit mode-dependent subpulse modulations, but of very different characters. PSR B0943+10’s B-mode displays a very regular pattern of drifting subpulses with repetition period $P_3 \approx 2P$, while in its Q-mode the emission is chaotic (Suleymanova & Izvekova 1984; Rankin & Suleymanova 2006). In the Q-mode of PSR B1822−09 a strong modulation with long period $P_{3,Q} = 46.55 \pm 0.88 \, P$ has been found, but not showing organised drifting. In its B-mode a weak modulation is reported with a longer and apparently harmonically-related periodicity of $P_{3,B} = 70 \pm 3 \, P$ (Latham et al. 2012). Further recent and detailed descriptions of its modal and pulse-sequence behaviour are given by Backus, Mitra & Rankin (2010); Latham et al. (2012) and Suleymanova, Lovendienne & Smirnov (2012).

The natural interpretation of the 180° separation seen in the Q-mode between the MP and IP is that PSR B1822−09 is an orthogonal rotator (see e.g. Hankins & Fowler 1986; Gil et al. 1994; Backus, Mitra & Rankin 2010) with the MP and IP being produced above the magnetic poles, and both poles detected by our line of sight. This is an important difference to PSR B0943+10, which is believed to be rotating close to alignment (≈ 9°) where our sight line continuously views one polar region. However, Dyks, Zhang & Gil (2005) and Malov & Nikitina (2011, 2013) pointed out that the MP-IP separation can also be explained in almost aligned rotator models. Given the importance of the geometry of PSR B1822−09 for the interpretation of the results of our X-ray/radio campaign and the absence of an exhaustive study of it in the literature, we have added such a study on the geometry of PSR B1822−09 in the Appendix. There we concluded that the existing evidence strongly points to PSR B1822−09 as having an orthogonal rotator geometry.

We carried out an X-ray/radio campaign on PSR B1822−09 with XMM-Newton and simultaneous radio observations primarily with the Westerbork Synthesis Radio Telescope (WSRT) at 1380 MHz, and supported by the Giant Metrewave Radio Telescope (GMRT) at 325 MHz and the Jodrell Bank Observatory Lovell telescope at 1420 MHz. We aimed at having two telescopes simultaneously observing the pulsar to both ensure that we can identify all

<table>
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<th>Right Ascension (J2000)</th>
<th>18$^{h}$25$^{m}$30$^{s}$630(5)</th>
</tr>
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<tbody>
<tr>
<td>Declination (J2000)</td>
<td>$-9\degree35\arcmin22\arcsec12(3)$</td>
</tr>
<tr>
<td>Epoch (TDB)</td>
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<tr>
<td>$\nu ,(Hz)$</td>
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<tr>
<td>$\ddot{\nu} ,(Hz , s^{-2})$</td>
<td>$-5.6(1) \times 10^{-25}$</td>
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<tr>
<td>Start (MID)</td>
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<td>End (MID)</td>
<td>56749</td>
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<td>Solar System Ephemeris</td>
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Numbers in parenthesis are the 1-$\sigma$ errors on the least significant digits.

In section 2 we present the radio observations and how we defined the radio-mode windows, and also report a surprising relationship found between structures in the distributions of mode durations in the B and Q modes and their underlying modulation periodicities $P_3$. In the subsequent sections we present the XMM-Newton X-ray observations (section 3), the X-ray Maximum-Likelihood spatial analysis of the sky maps, revealing a hard-spectrum source at a distance of only 5.1 from PSR B1822−09 (section 4), and the first detection of the X-ray pulsed signal from PSR B1822−09 folding in the timing analysis with an ephemeris derived from Lovell telescope radio monitoring of PSR B1822−09 (section 5). In section 6 we present the search for X-ray mode switching using a combined spatial and timing analysis. The spectral characterisation of the total, pulsed and steady unpulsed X-ray emissions is performed in section 7, followed by a summary of our findings in section 8 and a discussion of them in section 9. Finally, our overall conclusions are presented in section 10.

2 RADIO OBSERVATIONS AND RESULTS

2.1 WSRT radio observations and analysis

We observed PSR B1822−09 with the Westerbork Synthesis Radio Telescope (WSRT) using the tied-array mode, in which the individual signals of each dish are coherently summed to a single synthesised array beam by applying appropriate time and phase delays. Twelve of the fourteen WSRT 25-m dishes participated in the observations, and the PuMaII backend (Karuppusamy, Stappers & van Straten 2008) was used to record baseband voltage data from $8 \times 20$-MHz subbands together spanning frequencies of 1300–1460 MHz. We converted the baseband data to both folded (10-s sub-integrations) and single-pulse archives using the dspsr software suite (Hotan, van Straten & Manchester 2004; van Straten, 2016 RAS, MNRAS 000, 1–17

1 The rest were unavailable because of maintenance and the transition of the telescope to a new receiver system.

2 http://dspsr.sourceforge.net/manuals/dspsr/
Table 2. Radio observations of PSR B1822−09 in 2013 and 2014 with the WSRT, GMRT and Lovell telescope, together covering the simultaneous observations with XMM-Newton (Table 3).

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<tr>
<th>Telescope</th>
<th>Date yyyy-mm-dd</th>
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<th>End (UT) hh:mm</th>
<th>duration hours</th>
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<td>1380</td>
<td>13:01</td>
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<td>12:49</td>
<td>20:18</td>
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<td>13:17</td>
<td>21:36</td>
<td>8.33</td>
</tr>
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<tr>
<td></td>
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<td>06:22</td>
<td>10:22</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
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<td>10:38</td>
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<tr>
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</tr>
<tr>
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<td>18:12</td>
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<td>10:41</td>
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<td>Lovell</td>
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<td>23:45</td>
<td>8.83</td>
</tr>
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<td>1420</td>
<td>09:56</td>
<td>12:05</td>
<td>2.15</td>
</tr>
</tbody>
</table>

Demorest & Oslowski (2012), the data were cleaned of radio frequency interference (RFI) and the 8 20-MHz bands were combined into a single data cube of pulse phase, radio frequency and intensity (Stokes I). WSRT provided data during all (eight in total) XMM-Newton observing sessions, and covered practically all of the relevant X-ray windows (see Tables 2 and 3).

2.2 GMRT observations

Simultaneous PSR B1822−09 observations were carried out at the Giant Meterwave Radio Telescope (GMRT) for the first six observing sessions in September and October 2013, at 338 MHz on the first session and 624 MHz for the rest of the sessions (see Table 2). The GMRT is a multi-element aperture synthesis telescope (Swarup et al. 1991) consisting of 30 antennas distributed over a 25-km-diameter area which can be configured as a single dish in both coherent and incoherent array modes of operation. The observations discussed here used the coherent (or more commonly called phased array) mode (Gupta et al. 2000; Sirothia 2000). At these observing frequencies, the GMRT is equipped with dual linear feeds which are converted to left and right-handed circular polarisations via a hybrid. The dual polarisation signals are passed through a superheterodyne system and down converted to the baseband which are finally fed to the GMRT software backend (Roy et al. 2010). In the backend the FX correlator algorithm is implemented and in the phased array mode the voltage signals from all antennas are added in phase, which is finally recorded as a total power time series. We used a total bandwidth of about 33 MHz spread over 256 channels with time resolution of 0.122 ms.

The observing sessions at GMRT were such that only partial overlap, mostly during the earlier part of the observations, between WSRT, Lovell and XMM-Newton were possible. Even within the overlap region some parts of the data were not usable due to RFI or technical problems. At GMRT frequencies the strength of the interpulse is much more prominent than seen at higher frequencies, and hence the alternate emission between the IP and the PC for the Q and B modes, respectively, could be easily verified in these data. In regions of overlap with the WSRT observations, the mode switches were seen to correlate extremely well with what was derived based on the WSRT data. Fig. 1 shows as an example of the moding behaviour of PSR B1822−09 single pulse sequences measured with the GMRT at 624 MHz covering part of one of our XMM-Newton observations. The MP and PC are shown to simultaneously switch on/off on short time scales (typically minutes), while the IP switches on/off in anti-correlation with the MP and PC.

2.3 Lovell Telescope observations

We observed PSR B1822−09 using the 76 m Lovell Telescope at the Jodrell Bank Observatory on five occasions (Table 2) simultaneously with the XMM-Newton observations (Tables 3). Observations were made using a dual-polarisation cryogenic receiver at a central frequency of 1520 MHz with a total of about 380 MHz of
Figure 2. WSR T observation at 1380 MHz of PSR B1822−09 for 6.8 hours, 6 October 2013. From top to bottom: cumulative pulse profile with indicated in colour the PC (purple), MP (green), off-pulse region / “Noise” (orange) and IP (yellow) phase windows, followed by a zoom-in on the PC and MP as a function of time; then, the signal-to-noise ratios (S/N) of the detections in time bins of 10s of the PC, the MP and the IP. The x-axis in the bottom 4 panels gives the number of 10-s bins. The PC exhibits a very clear on/off switching, and has been used to define the bright (B, pink) and quiet (Q) mode intervals.

useful bandwidth after removal of known and intermittent radio-frequency interference. The incoming analogue data was sampled, dedispersed and folded in real-time using two different pulsar backends, the digital filter bank (DFB) and the coherent dedispersion backend called the ROACH (Bassa et al. 2016). The DFB data filtered the bandwidth into 0.5 MHz wide channels and incoherently dedispersed and folded into 10-s sub-integrations using the same ephemeris as used for the WSRT observations. The ROACH data were coherently dedispersed and two data products were generated: folded profiles with 10-s sub-integrations with 1 MHz wide channels and single-pulse archives with 4 MHz wide channels. The coherent dedispersion used the dspsr (van Straten & Bailes 2011) software and post-processing made use of the PSRCHIVE software suite (Hotan, van Straten & Manchester 2004; van Straten, Demoest & Oslowski 2012).

The Lovell telescope data overlapped with almost the entire WSRT data set and the XMM-Newton observing windows and so was used as an independent check of the detailed analysis of the WSRT data. A series of randomly chosen mode transitions were identified in the Lovell data, using either, or both, of the single pulse and 10-s subintegration data and compared with those transitions identified in the WSRT data. This confirmed the times of the mode transitions and because of the different offsets between the start times of the 10-s sub-integrations and single pulses could be used to estimate the maximum number of pulses which might be attributed to the incorrect mode.

2.4 Mode determinations using WSRT, Lovell & GMRT data

In our analysis we make the basic assumption that, at any given time, PSR B1822−09 is either emitting in the B or Q mode. While this assumption seems to be strictly true for most mode-switching pulsars and was formerly thought to be true for PSR B1822−09, Latham et al. (2012) found evidence for short intervals of mixed modes in PSR B1822−09 in the vicinity of the transitions from one mode to the other with a duration of a few pulses. These intervals, however, are sufficiently short that they have little effect on our analysis.

Mode determination was based primarily on the WSRT data set because it provided the most complete overlap with the XMM-Newton sessions. The Lovell and GMRT data provided checks of the WSRT results, and the strategy of using 3 radio telescopes in parallel was to provide redundancy in the case of technical problems at one of the observatories during one of the XMM-Newton sessions (fortunately no such issues affected the general observing campaign).

Using WSRT data, we defined for each observation pulse-phase windows encompassing PSR B1822−09’s pulse PC, MP, IP and a reference off-pulse region (Figure 2). For each 10-s sub-integration (equivalent to ~ 13 pulse periods of $P = 0.769$ s) we measured the S/N of the PC, MP and IP (Figure 2). We found that setting a S/N threshold on the precursor emission provided a robust and automated method of separating the B and Q-mode intervals – despite the low number of pulses per 10-s sub-integration. The
presence of PC emission is in anti-correlation with the presence of the IP, but, the relative weakness of the IP at 1.4 GHz observing frequencies makes it a comparatively less reliable mode indicator. While PSR B1822−09 can sometimes switch modes on < 10-s timescales, such switches were not resolvable using this method. These intervals, however, are sufficiently short that they have negligible effect on the results of the X-ray analysis.

The first radio observations took place in Sept/Oct 2013 and comprised six sessions of between 7 and 8.5 hours long (see Table 2), virtually contiguous with the times of the XMM-Newton observations listed in Table 3, amounting to a total of 162.620 ks (211,500 pulses). On the successive dates the Q-mode percentage was 65.1%, 62.4%, 60.6%, 62.9%, 66.6%, 66.9%, with an overall figure of 64.1%. The second set of observations occurred on March 10 and 12 in 2014 (Table 3). There were two sequences on each day, and the short second sequence of both had to be truncated (after 4 ks and 2.7 ks respectively) as the pulsar was setting and the mode resolution poor. Altogether the useful observations amounted to 35.340 ks (46,000 pulses). The total Q-mode percentage of these observations was 63.5%, giving a composite figure of 63.9% for 2013 and 2014 together.

The total number of mode changes was 952, implying an average of one mode change every three and a half minutes (208 s). The average Q-mode sequence was 270 s (∼ 347 pulses), B-mode sequence 150 s (∼ 195 pulses). The longest Q-mode was 4420 pulses (3400 s), recorded on 28 Sept, and the longest B-mode was 971 pulses (670 s) in the same observation and directly after the aforementioned long mode. Note that in a single 8-hr observation (i.e. comparable with each of our observations) Latham et al. (2012) found examples of both Q- and B-mode lengths greater than those recorded here. An explanation for this possible discrepancy might be that some of our long mode windows are interrupted by a short (single 10-s integration) switch to the other mode that could in some cases be spurious and caused by RFI. For example, in Figure 2 there is a very short “B-mode” instance that breaks up what would be an otherwise longish Q-mode sequence. Alternatively, such short mode interruptions might have been overlooked by Latham et al. (2012).

It is relevant to note that Lyne et al. (2010) studied the spin down of PSR B1822−09 in a sample of 17 pulsars over ∼ 20 years. The value of the ν of PSR B1822−09 averaged over typically 50 days was found to change between two well-defined values, correlated with changes of the average pulse profile: for the high-ν state, the precursor is weak and the interpulse is strong, with the reverse occurring for the smaller-ν state. This correlation of large changes in ν with pulse shape changes, found for a substantial number of pulsars, suggests a change in magnetospheric particle current flow. We verified that during all eight observing sessions of our campaign, the average ν values of PSR B1822−09 were similar, not in a high-ν | state.

2.5 Mode-length Histograms

Fig. 3 shows a histogram of the lengths of the intervals between the approximately 952 mode changes observed in 55 hours, sampled every 10 s. If these were occurring at random it would imply a probability of 952/(55×60×6)=0.048 per 10 s. The associated exponential distribution describing the outcome of a Poisson process would be

\[ N(x) = 952 \times 0.048 \exp(-0.048x) \]  

Note that this curve closely matches the observations apart from the spike in the first single bin of 10 s (truncated in the figure), which contained 98 modes.

Fig. 4(upper) shows the histogram of the ≈ 952/2 = 476 Q-mode lengths. In addition to the ultra-short modes of less than 20 s, we note a narrow peak at short lengths and a long trailing tail, suggesting the possibility of two kinds of Q-mode sequences (or three if we include the ultra-short). Fig. 4(lower) shows the histogram of the B-mode lengths. Apart from the spike in the first 10 s, it is noticeable that the distribution has two equal peaks (at ~ 120 s and ~ 240 s) with a shallow dip between them. There is also a much shorter tail towards longer mode durations than in the Q-mode distribution.

Both the histograms of Fig. 4 have been overlaid with vertical red and blue lines which mark multiples of the central modulation periodicities (P3) found by Latham et al. (2012) in 325 MHz observations of long Q- and B-mode sequences. Thus P3,Q, expressed in terms of the rotation period P, is 46.55P (35.8 s) for the Q-mode and P3,B = 70P (53.6 s) for the B-mode, close to a ratio of 2:3. The markers appear to coincide with features in the histograms.

In Fig. 4(upper) for the Q-mode the first (red) line closely aligns with the initial peak of the distribution, implying that the most common length for a Q-mode sequence, if one ignores the larger peak at the shortest time scales, is the same as the modulation timescale found in longer Q-mode sequences. It also suggests that all Q-mode sequences start at about the same phase of modulation.

We previously noted that both Figures 3&4 exhibit initial peaks for mode lengths ≤ 20 s and remarked earlier that mode switches on < 10-s timescales were not resolvable. In addition, RFI can mimic such short mode lengths and could be responsible for the initial peaks. In order to investigate how significant these short mode-lengths might be for our analysis, we generated cumulative distributions of the fraction of the total number of pulses (∼ fraction of total observation time) in the Q and B mode as a function of mode length (see Fig. 5). This figure shows that the contribution of these short-lengths intervals amounts to < 1% of the total number of pulses, thus can be ignored in the following discussion of the ra-
Note that red lines (odd multiples of $P_3$ for $Q$, even for $B$) tend to coincide with maxima, and blue lines (even multiples of $P_3$ for $Q$, odd for $B$) with minima. Since the $P_3$s of $Q$ and $B$ (35.8 s and 53.8 s respectively) are resonant (2:3) the red lines at $3 \times 35.8 = 2 \times 53.8 = 107.4$ s and the red/blue lines at $2 \times 107.4 = 215.4$ s are common to both histograms.

In the Q mode, at multiples of $P_{3,Q}$ little can be discerned as peaks or minima in the histogram, possibly because the decline in the height of the histogram is rapid and the bin size will smooth any features. However, a clear minimum appears around $6 \times P_{3,Q} = 215.2$ s. For this reason we have given the $P_{3,Q}$ lines alternating colours of red and blue, speculating that there may be an unresolvable underlying periodicity of $2 \times P_{3,Q}$, corresponding to what is found in the B-mode.

In the B-mode histogram of Fig. 4 (lower) a minimum appears at the $P_{3,B} = 70P = 53.8$ s (blue line), so B-mode sequences of this length are rare in the observations. Overwhelmingly, they are found near the first two multiples of $2 \times P_{3,B}$, i.e. 107.6 s and 215.2 s (red lines), separated by a further minimum at $3 \times P_{3,B} = 161.4$ s (blue line). This strongly supports the suggestion by Latham et al. (2012) that the precursor PC is modulated at $2 \times P_{3,B}$ and is weak where the MP is weak (Latham et al. 2012, see their Figure 12). As with the Q-mode, the presence of peaks and troughs in the histogram implies that the B-mode starts at roughly the same phase of its modulation.

Figure 4 Upper figure: the histogram of the Q-mode lengths. Lower figure: the equivalent histogram for B-mode. The red and blue lines show successive multiples of the $P_3$ for each mode reported by Latham et al. (2012). Note that red lines (odd multiples of $P_3$ for $Q$, even for $B$) tend to coincide with maxima, and blue lines (even multiples of $P_3$ for $Q$, odd for $B$) with minima. Since the $P_3$s of $Q$ and $B$ (35.8 s and 53.8 s respectively) are resonant (2:3) the red lines at $3 \times 35.8 = 2 \times 53.8 = 107.4$ s and the red/blue lines at $2 \times 107.4 = 215.4$ s are common to both histograms.

Figure 5. Cumulative distributions of the fraction of the total number of pulses, in separately the Q and B mode, as a function of mode length of PSR B1822-09.

dio characteristics, as well as for the accumulation of X-ray events in the Q and B modes.

In the Q mode, at multiples of $P_{3,Q}$ little can be discerned as peaks or minima in the histogram, possibly because the decline in the height of the histogram is rapid and the bin size will smooth any features. However, a clear minimum appears around $6 \times P_{3,Q} = 215.2$ s. For this reason we have given the $P_{3,Q}$ lines alternating colours of red and blue, speculating that there may be an unresolvable underlying periodicity of $2 \times P_{3,Q}$, corresponding to what is found in the B-mode.

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Note that the cycle of maxima and minima in the two modes complement one another, with maxima in one roughly coinciding with minima in the other. In fact the B-mode maximum and Q-mode minimum at $\sim 215.2$ s ($= 280P$) precisely coincide since $1/280$ is half the beat frequency of $1/46.55$ and $1/70$.

The important conclusion to be drawn from Fig. 4 is that for the first time in a mode-switching pulsar a clear yet subtle relationship has been found between the duration of its modes and a known underlying modulation timescale of the intensities within the modes. It is all the more remarkable that in Fig. 3 the combined histogram of both modes suggests – possibly coincidentally – an overall random distribution of the mode lengths.

3 XMM-NEWTON X-RAY OBSERVATIONS

Before our work, only upper limits were published on X-ray emission from PSR B1822$-$09 (Alpar et al. 1995; Slane & Lloyd 1995). However, we found in the archives of XMM-NEWTON a short observation with an effective on-source exposure of 4.8 ks. We clearly detected the source at a significance level of 6.9σ (energies 0.2 – 2 keV) with a count rate slightly higher than what we had measured for the time-averaged count rate from PSR B0943+10, enabling us to propose this campaign. Later, Prinz & Becker (2015) also analysed this observation and found the source as well.

We obtained six XMM-NEWTON X-ray observations of PSR B1822$-$09 in September and October 2013, and two in March 2014 with durations between $\sim 6$ and 9 hours (see Table 3). In this work we used only data obtained with the EPIC instrument aboard XMM-NEWTON, which consists of one camera based on Pn CCDs (Strieder et al. 2001), the Pn, and two cameras based on MOS CCDs (Turner et al. 2001), MOS 1 and MOS 2. During all observations, the Pn camera was operated in Large Window mode, which provides a time resolution of 47.7 ms, and the MOS cameras were operated in Small Window mode with a time resolution of 0.3 s. For the three cameras we used the thin optical filter. The EPIC Pn count rate in the 10-12 keV energy range was always significantly below 1.2 counts s$^{-1}$, indicating that our observations were not affected.
by increased particle backgrounds due to soft proton flares. The total lifetime (dead time corrected exposure) for the Pn, MOS 1, and MOS 2 cameras are given in Table 4.

4 X-RAY SPATIAL ANALYSIS

In the spatial analysis we apply a two-dimensional Maximum Likelihood (ML) method using our knowledge of the two-dimensional point-source signature (the point spread function; PSF), and taking into account the Poissonian nature of the counting process. The PSF is fitted to the measured two-dimensional count distribution on top of a background structure, assumed to be flat, at the known position of the source or on a grid of positions in the source region when the source position is not known. Typical fit-region sizes are of the order of 30-60″.

At first the events a are sorted in counts skymaps with two-dimensional pixels typically of size 2″× 2″. To obtain the number of source counts the following quantity, $L = \ln \left( \prod_{i,j} \mathcal{F}_{ij} \left( \Phi_{N_{ij}} \exp(-\mu_{ij}) / N_{ij} \right) \right) = \sum_{i,j} N_{ij} \ln(\mu_{ij}) - \mu_{ij} - \ln(N_{ij})$, where $\mu_{ij} = \beta + \sigma \cdot P S F_{ij}$ is the expectation value for pixel $(i, j)$ and $N_{ij}$ the number of counts measured in pixel $(i, j)$.

a Each event $i$ is characterised by its (barycentred) arrival time $t_i$, spatial coordinates $x_i, y_i$, energy $E_i$, event pattern $\xi_i$ and flag $F_i$. We used $\xi_i = [0, 4]$ and flag $F_i = 0$ for both Pn and MOS.

The ML spatial analysis showed that the X-ray distribution can be explained with the presence of two point sources. However, given the 6″ FWHM PSF of XMM-Newton and the measured separation of $(5.1 \pm 0.5)″$, we cannot exclude that the neighbouring excess is slightly extended. Of 13 nearby middle-aged pulsars with XMM-Newton and/or Chandra X-ray observations 6 have prominent X-ray Pulsar Wind Nebulae (PWNe), 2 have very faint PWNe and for 4 there are no detections reported yet in current data (Posselt, Spence & Pavlov 2015). For example, the most well-known nearby middle-aged pulsar Geminga exhibits a very prominent PWN, discovered by Caraveo et al. (2003) and more recently studied in most detail by Pavlov, Bhattacharyya & Zavlin (2010) exploiting deep Chandra observations. The latter authors confirmed that the Geminga PWN has three tail-like components with patchy structures, including three possibly moving blobs. The spectra of the PWN elements appeared to be rather hard with photon index ∼1. Our new source might be such a hard-spectrum element of a PWN.

4.1 Nature of nearby hard source?

The ML spatial analysis showed that the X-ray distribution can be explained with the presence of two point sources. However, given the 6″ FWHM PSF of XMM-Newton and the measured separation of $(5.1 \pm 0.5)″$, we cannot exclude that the neighbouring excess is slightly extended. Of 13 nearby middle-aged pulsars with XMM-Newton and/or Chandra X-ray observations 6 have prominent X-ray Pulsar Wind Nebulae (PWNe), 2 have very faint PWNe and for 4 there are no detections reported yet in current data (Posselt, Spence & Pavlov 2015). For example, the most well-known nearby middle-aged pulsar Geminga exhibits a very prominent PWN, discovered by Caraveo et al. (2003) and more recently studied in most detail by Pavlov, Bhattacharyya & Zavlin (2010) exploiting deep Chandra observations. The latter authors confirmed that the Geminga PWN has three tail-like components with patchy structures, including three possibly moving blobs. The spectra of the PWN elements appeared to be rather hard with photon index ∼1. Our new source might be such a hard-spectrum element of a PWN of PSR B1822-09, but a deep high-spatial resolution Chandra observation is required to resolve the ambiguity of whether we are detecting in X-rays an extended structure or a compact object.

To investigate this further, we searched for a counterpart at lower energies by scrutinising the optical/IR archives. We found deep (almost) on-source exposures performed on June 15 and July 20, 2004 by the ESO 3.6 m NTT equipped with the 5.5′ × 5.5′ CCD imaging camera SUSI2. We downloaded several images taken through different filters and correlated these with the UCAC3 catalogue for astrometric calibration yielding accurate positions at 0″.1 level. In the 60-s, 600-s and 800-s exposures (R-, H-, and V-bands, respectively) we found no candidate counterpart at the location of the hard source, nor at the position of PSR B1822-09, down to a
limiting magnitude in the V-band of $\sim 25.0$, adopting an input spectrum of a A0 V star.

Independent of its nature, the discovery of this nearby hard source requires in our further analysis, notably when source spectra are derived, that both sources are fitted simultaneously for energies above 1.4 keV. For the XMM-Newton PSF and the low counting statistics of the new source, it suffices to assume a point-source structure.

5 X-RAY TIMING ANALYSIS

We performed timing analyses by selecting Pn and MOS 1&2 events detected within a 20″ aperture around the X-ray position of PSR B1822−09. The times of arrival were converted to arrival times at the Solar System Barycentre and folded upon the ephemeris of PSR B1822−09 given in Table 1. Fig. 7a shows the discovery of pulsed X-ray emission from PSR B1822−09 with the detection of a broad pulse in the energy band 0.2−1.4 keV at a significance of 9.6$\sigma$ (Buccheri et al. 1983, $Z^2$ value). The measured X-ray profile can be well fitted with a sinusoid and reaches its maximum at phase 0.094 ± 0.017, with the radio main pulse, which is also sinusoidal in shape, peaking at phase 0 (indicated in Fig. 7a). The radio precursor precedes the radio main pulse, and the X-ray pulse lags the radio. Furthermore, we do not see a pulse or local maximum at the phase of the interpulse, something we might expect for the geometry of an orthogonal rotator. However, if there is a weaker X-ray pulse at the phase of the interpulse, also sinusoidal in shape, the summed profile with the main pulse would hide the X-ray interpulse and result in a phase distribution as shown in Fig. 7a. Therefore we cannot state at this stage of the analysis, whether the measured distribution is due to two broad X-ray pulses, a strong one peaking close to the phase of the main pulse, and a weaker one peaking around the phase of the interpulse, or that we measure an unpulsed level of steady emission with a superposed single pulse component. In the spectral analysis we will address these two options.

The pulsar-phase distribution in Fig. 7a contains, in addition to pulsar-source counts (pulsed plus unpulsed), a flat celestial background level. This background level can be suppressed by applying phase-resolved spatial analysis: for each phase bin count sky maps are produced and with the two-dimensional ML method the number of source counts is determined per phase bin. This approach gives the distribution shown in Fig. 7b for the integral energy range 0.2−1.62 keV. All counts detected from PSR B1822−09 (pulsed plus unpulsed) are contained in this pulsar-phase distribution. Therefore, the number of source counts is much larger than in Fig. 7a, because the latter contains only source counts (plus sky-background counts) detected within a 20″ aperture around the PSR B1822−09 position, while the two-dimensional tail of the PSF extends well beyond the applied aperture. As a result, the energy range over which the pulse profile is detectable, widens somewhat.

We applied the phase-resolved spatial analysis (all Pn and MOS 1&2, observations) in nine differential energy intervals between 0.2 and 10 keV. Fig. 8 shows the resulting pulse-phase distributions. From 0.2 to 1.6 keV between $\sim 300$ to 700 source counts (pulsed plus unpulsed) are detected per energy interval, while above 1.6 keV the distributions are consistent with zero counts from PSR B1822−09 (the zero level is indicated by the broken line). This figure also shows that there is no evidence for a variation of the pulse shape with energy over the 0.2 to 1.6 keV band. Namely, for all phase distributions below 1.6 keV fits with sinusoids, with maximum at the same phase as shown in Fig. 7, above flat unpulsed source-count levels nicely represent the data, as is shown in the figure. Fig. 8 shows already by eye how the relative contributions of pulsed and unpulsed emission vary with energy.
β + φ events now according to their spatial (x,y) and pulse phase. Sorting the information of the events (three-dimensional approach), by assuming the ML method by taking into account also the pulse-phase across the values we can write for the expectation value of bin (i,j,k):

\[ \mu_{ijk} = \beta + \sigma_u \cdot PSF_{ij} + \sigma_p \cdot PSF_{ij} \cdot \Phi_k \]

In this formula the value of the normalized pulse profile at bin \( k \) is represented by \( \Phi_k \), while \( \sigma_u \) and \( \sigma_p \) correspond to the unpulsed and pulsed component scale factors. From \( \sigma_u \) and \( \sigma_p \), the pulsed fraction \( \eta \) can be determined as \( \eta = 1/(1 + (N_b - \sigma_u/\sigma_p)) \), with \( N_b \) the number of bins of the normalized pulse profile.

Applying the three-dimensional ML method we derived the pulsed fraction as a function of energy, shown in Fig. 9. At low energies of \( \sim 0.3 \) keV the pulsed fraction starts at a level of \( \sim 0.15 \) and reaches a value of \( \sim 0.6 \) around 1 keV. This clearly shows that the X-ray spectrum of the pulsed signal is much harder than that of the unpulsed emission. In § 7.2 we will derive the corresponding spectral parameters.

### 6 X-RAY MODE SWITCHING

We have sorted the events collected in the radio Q- and B-mode time windows, respectively, as determined in § 2.4 using our simultaneous radio observations. The accumulated lifetimes in the two radio modes of the MOS 1, MOS 2 and Pn cameras are listed in Table 4. For both modes we applied the two-dimensional ML method in the 0.4-1.4 keV band on the pulsar position using the Pn and MOS 1&2 data and determined the total pulsar count rates. It turned out that there is no significant difference in the total X-ray count rates of the Q and B modes, namely \( 0.0132 \pm 0.0005 \) and \( 0.0126 \pm 0.0006 \), respectively. In order to check whether there is an indication for mode switching in the fluxes of the pulsed and unpulsed components, in the X-ray pulse shape, we constructed for the Q- and B-mode data pulse profiles of PSR B1822–09 applying phase-resolved spatial analysis, thus modelling out the celestial background. The pulse profiles (0.4-1.4 keV) are shown in Fig. 10 for the Q mode (solid line) and B mode (broken line). Applying the Kolmogorov-Smirnov test gives a probability that the two profiles are drawn from the same parent distribution of 97.5%. The differences between the two profiles are shown in the lower figure. This leads to the conclusion that we find no evidence for mode switching in the pulse profile of PSR B1822–09 (pulse shape and flux), nor in the flux of the unpulsed emission.

In Fig. 4 we showed that the mode-length distributions of the Q and B modes are very different. They exhibit different structures and timescales of the radio intensities within the modes. Although we do not have an explanation for this intriguing relationship, and do

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**Figure 7.** Pulse profile of PSR B1822–09, using data from XMM-Newton Pn and MOS 1&2 detectors for all 8 observations. Left, (a), derived by phase folding of event arrival times (see text) for energies 0.4-1.4 keV selecting only events within an aperture of \( 20'' \); detection significance 9.6σ. Right, (b), derived by phase-resolved imaging (see text) for energies 0.2-1.62 keV, including all detected source events in the counts map; sky background has been modelled out. The radio main pulse peaks at phase 0. The solid-line profiles show fits with sinusoids peaking at phase 0.094 ± 0.017. The arrows in Fig 7a mark the phases of the radio main pulse (MP), interpulse (IP) and precursor (PC).

**Table 5.** PSR B1822–09 count rates (\( \times 10^2 \)) in the energy band 0.4–1.4 keV for different selections on mode lengths in the Q and B modes.

<table>
<thead>
<tr>
<th>Mode length</th>
<th>Total 10–210 s</th>
<th>( \geq 210 ) s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q mode</td>
<td>1.32 ± 0.05</td>
<td>1.41 ± 0.13</td>
</tr>
<tr>
<td>B mode</td>
<td>1.20 ± 0.06</td>
<td>1.59 ± 0.35</td>
</tr>
</tbody>
</table>

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Figure 8. Pulse profiles of PSR B1822−09 in differential energy intervals between 0.2 and 10 keV, obtained from phase-resolved spatial analyses using XMM-Newton Pn and MOS 1&2 data for all observations listed in Table 3. The solid-line profiles show fits with a sinusoid centred on the phase of the X-ray pulse for the integral 0.4–1.4 keV energy interval. The radio main pulse peaks at phase 0. The celestial background, assumed to be flat, is modelled out. The y-axis gives per phase bin the derived number of pulsed plus unpulsed counts from the point source.

not know whether a relation with the X-ray flux can be expected, we made selections on the apparent components in the mode-length distributions to see whether we find variations in X-ray flux/count rate. In the Q-mode-length distribution the initial spike below 10-s duration does not contain a sufficient number of counts, therefore we selected events detected in the narrow peak at \(\sim 50\) s between 10 s and the minimum at \(\sim 210\) s (\(\sim 6 \times P_3\)), and events in the trailing tail above 210 s. In the B-mode distribution we selected events in the initial spike until the minimum at \(\sim 50\) s (\(\sim 70P\)), the next component between 50 s and 160 s (\(\sim 3 \times P_3\)), and finally all events detected in mode intervals with lengths longer than 160 s. The derived X-ray count rates for energies 0.4–1.4 keV are given in Table 5 in comparison with the count rates for the total Q and B modes (no selection on mode length). For both modes, the count rates in the differential mode-length intervals are within one \(\sigma\) of the count rates measured for the total Q and B mode data, respectively. Therefore, we do not see evidence for a relationship between the X-ray count rate and an underlying modulation time scale of the radio intensities within the modes.

7 SPECTRAL ANALYSIS
7.1 Spectrum total emission of PSR B1822−09

We first derived the spectral parameters for the total emission from PSR B1822−09 between 0.2 and 10 keV using all the observations listed in Table 3 the Pn and MOS 1&2 data and performing the two-dimensional ML analysis. We applied the optimisation scheme introduced in Section 4 for the spatial analysis for a grid of user-defined energy windows between 0.2 and 10 keV, again adopting for the event pattern \(\xi = [0, 4]\) and for the flag \(F = 0\). For energies below 1.4 keV we fitted with one source at the position of PSR B1822−09 and for energies above 1.4 keV we in-
Table 6. Spectral fits with power-law (PL) and black-body (BB) models to the total emission spectrum of PSR B1822−09 over the energy range 0.2-10 keV using Pn and MOS 1&2 data of all observations listed in Table 3. The flux values are derived in a maximum-likelihood spatial analysis of sky maps for differential energy intervals.

<table>
<thead>
<tr>
<th>Model</th>
<th>Fit par.</th>
<th>PL Total</th>
<th>BB Total</th>
<th>BB+PL Total</th>
<th>BB+BB Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_H \times 10^{-21})</td>
<td>3.77^{+0.26}_{-0.23}</td>
<td>1.05^{+0.12}_{-0.12}</td>
<td>2.83^{+0.31}_{-0.25}</td>
<td>2.40^{+0.43}_{-0.41}</td>
<td></td>
</tr>
<tr>
<td>(\alpha_{PL} \times 10^6)</td>
<td>11.04^{+1.06}_{-1.04}</td>
<td>6.05^{+1.64}_{-1.70}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Gamma)</td>
<td>-6.32^{+0.30}_{-0.34}</td>
<td>-5.16^{+0.60}_{-0.67}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{PL} \times 10^{14})</td>
<td>8.19^{+0.20}_{-0.22}</td>
<td>2.59 ± 0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha_{BB1})</td>
<td>0.016^{+0.003}_{-0.002}</td>
<td>0.27^{+0.24}_{-0.12}</td>
<td>0.43^{+0.18}_{-0.14}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kT_1)</td>
<td>0.126^{+0.003}_{-0.004}</td>
<td>0.085^{+0.007}_{-0.007}</td>
<td>0.085^{+0.004}_{-0.004}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(R_{BB1})</td>
<td>393^{+37}_{-25}</td>
<td>1616^{+718}_{-359}</td>
<td>2039^{+389}_{-365}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{BB1} \times 10^{14})</td>
<td>1.70 ± 0.04</td>
<td>2.27 ± 0.25</td>
<td>3.2 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha_{BB2})</td>
<td>1.21^{+0.20}_{-0.19}</td>
<td>10^{+12}_{-5}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kT_2)</td>
<td>0.187^{+0.026}_{-0.023}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(R_{BB2})</td>
<td>98^{+48}_{-28}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{BB2} \times 10^{14})</td>
<td>0.65 ± 0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\chi^2 / dof)</td>
<td>1.42 / 33-3</td>
<td>1.86 / 33-3</td>
<td>1.24 / 33-5</td>
<td>1.14 / 33-5</td>
<td></td>
</tr>
</tbody>
</table>

Units: \(N_H\) in cm\(^{-2}\); \(\alpha_{BB}\) in ph/cm\(^2\)s/(keV)\(^3\); \(kT\) in keV; Fluxes are unabsorbed for the 0.5-2 keV band in erg/(cm\(^2\)s); \(R_{BB}\) in meters adopting a source distance of 1 kpc; \(\alpha_{PL}\) in ph/(cm\(^2\)s) at 1 keV

Table 6: Spectral fits with power-law (PL) and black-body (BB) models to the total emission spectrum of PSR B1822−09 over the energy range 0.2-10 keV using Pn and MOS 1&2 data of all observations listed in Table 3. The flux values are derived in a maximum-likelihood spatial analysis of sky maps for differential energy intervals.

Figure 9. PSR B1822−09: pulsed fraction as a function of energy as derived from a three dimensional ML analysis (see text). The energy dependence shown, indicates that between 0.2 and 2 keV the spectrum of the pulsed emission is harder than the spectrum of the unpulsed emission.

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included the second source as well. This resulted in background free source count numbers per energy interval (EPIC Pn and MOS 1&2 treated separately). These source counts were converted to source flux values in a forward folding spectral fitting procedure assuming a spectral model and using proper response (arf and rmf files) and lifetime (dead time corrected exposure) information.

An important parameter in this spectral analysis is the absorbing column density towards PSR B1822−09, \(N_H\). An estimate of this parameter is not yet published. Using HI line measurements of pulsars Johnston et al. (2001) determined an upper limit to the distance of PSR B1822−09 of 1.9 kpc, thus a location in front of the Sagittarius-Carina arm. We estimated that this would indicate an upper limit to \(N_H\) of \(N_H \sim 3 \times 10^{21} \text{cm}^{-2}\). A number of papers quote a lower distance, e.g. 0.9 kpc (Zou et al. 2005; Prinz & Becker 2015). Therefore, we first treated \(N_H\) as free parameter in our spectral fits to verify whether its value from the X-ray spectral analysis will indeed be below the upper limit.

We first produced fits to the total source-count spectrum with a single power law (\(\alpha E^\Gamma\)) and a single blackbody. Both fits are not acceptable. The power-law index has an unphysical value \(-6.32^{+0.30}_{-0.34}\) and the single blackbody gave a poor fit with \(\chi^2 = 1.86\) (for 31 degrees of freedom, dof). A fit with a blackbody plus power law was also not acceptable with an unphysical value of \(\Gamma\) of \(-5.1^{+0.60}_{-0.67}\). A fit with two blackbodies gave an excellent fit with \(\chi^2 = 1.14\) (for 28 dof) and a very reasonable value for \(N_H = 2.40^{+0.43}_{-0.42} \times 10^{21} \text{cm}^{-2}\). In conclusion, the total spectrum of PSR B1822−09 can successfully be described as the sum of two
blackbody components, a cooler blackbody with $kT \sim 0.083$ keV ($T \sim 0.96$ MK) and large hot spot radius of $\sim 2$ km, and a hotter blackbody with $kT \sim 0.187$ keV ($T \sim 2.2$ MK) and a radius of only $\sim 100$ m. Fig. 11a shows the excellent fit to the total spectrum with the two blackbodies. Table 6 lists all spectral parameters with their uncertainties of the discussed fits to the total emission. The best estimate of $N_H$ from this X-ray analysis is for the two-BB fit ($2.40 \times 10^{21}$ cm$^{-2}$).

### 7.2 Spectra of the pulsed and unpulsed emissions of PSR B1822–09

In § 5 we introduced the three-dimensional ML approach after we had shown that there is no evidence for pulse shape variations over the XMM-Newton energy range. In this approach the ML analysis is applied in the 3D data space by axes for the defined sky coordinates and pulsar phase. The spatial PSF is the point source signature in the skymaps for differential energy intervals and the sinusoid the shape of the pulse profile in all differential energy bins. The complementary pulsed and unpulsed source counts per differential energy interval are simultaneously determined. Similar to what has been done for the total spectrum, these source counts were converted to source flux values in a forward folding spectral fitting procedure assuming a spectral model and using proper response (arf and rmf files) and lifetime (dead time corrected exposure) information.

In order to compare the fit parameters independent of variations in $N_H$, we fixed $N_H$ in the following fits of the pulsed and unpulsed emission to the value obtained for the total emission with the double BB: $2.40 \times 10^{-21}$ cm$^{-2}$. First we fitted the pulsed spectrum with a single power law, and could reject this shape (index $\Gamma = -4.3$ with $\chi^2 = 1.87$ for 7 dof). However, a single BB rendered an acceptable fit ($\chi^2 = 1.37$ for 7 dof) with $kT = 0.136^{+0.030}_{-0.009}$ keV and hot spot radius $R = 256^{+42}_{-52}$ m. The latter two values are in between those of the hot and cool components in the two-BB fit to the total emission (see 2nd column of Table 7). When we then made a fit with a double-BB to the pulsed emission, we find within the statistical significance the same $kT$ values for a hot and a cool component (4th column) as for the total emission (2nd column). Although statistically not required, the double-BB fit thus renders a consistent picture with the same spectral components as obtained for the total emission. For further comparison, we also fixed the two $kT$ values to the best-fit values of the total emission (see the 5th column of Table 7). This interestingly shows that the flux of the hot component of the pulsed emission, with small radius of $84 \pm 5$ m, is consistent with being entirely responsible for the flux of the hot component in the total emission. The cool component of the pulsed emission contributes only a small fraction ($14 \pm 3$%) to the flux of the cool component of the total emission. This indicates that the cool component ($kT = 0.083$ keV) should primarily be found in the unpulsed/steady component.

For the spectrum of the unpulsed emission we could immediately rule out a power-law shape ($\Gamma = -5.84$). A single-BB model gave a poor fit ($\chi^2 = 2.06$ for 7 dof, or 5% probability for the fit to be acceptable), but with, interestingly, the same cool $kT_1$ value of $0.083 \pm 0.003$ keV and hot-spot radius of $\sim 2$ km as found for the cool component in the total fit. To see whether there is also room for the above derived hot component, we added $kT_2$ fixed at 0.187 keV. The fit improved ($\chi^2 = 1.81$ for 7 dof), but there is only marginal evidence for this hot component; the flux has a 50% error. The spectral fit parameters for the unpulsed-emission spectrum are also listed in Table 7.

Fig. 11b & c show the derived unabsorbed spectra of the pulsed and unpulsed emission, respectively. The best fits with two BB components (fixed at $kT = 0.083$ keV and $kT = 0.187$ keV) are shown, as well as the individual contributions of the cool and hot components. We obtained a consistent picture from this spectral analysis with the hot ($kT = 0.187$ keV) BB component in the total emission being due to the events in the pulse at the position of the main pulse above the flat/unpulsed level. There is not more than a hint for this hot component to be present in the unpulsed emission. Furthermore, the cool BB component with $kT = 0.083$ keV and radius of $\sim 2000$ m is almost entirely due to the unpulsed emission. In this case, such a cool component is also present in the pulsed emission but with smaller radius of $\sim 800$ m and contributes only a small fraction of $\sim 14\%$ to the cool component in the total emission.

### 8 SUMMARY

Thanks to the long dead-time-corrected exposure of $\sim 200$ ks with XMM-Newton, together with the unprecedentedly long simultaneous WSRT radio coverage of PSR B1822–09 we could study its properties in great detail. We first present a summary of the new findings of our X-ray radio campaign.

- In $\sim 198$ ks of useful radio observations 952 mode switches of PSR B1822–09 were detected with 63.9% of the pulses in the Q mode. The average Q-mode length was 270 s ($\approx 347$ pulses), and average B-mode length 150 s ($\approx 195$ pulses).

- The histograms of the radio Q-mode and B-mode lengths exhibit very different structures with maxima in one roughly coinciding with minima in the other, located at multiples of the modulation periodicity $P_h$. For the first time in a mode-switching pulsar...
Figure 11. Unabsorbed X-ray photon spectra of PSR B1822−09. Panel A: Total spectrum from spatial analyses of count skymaps with flux values independently derived for XMM-Newton EPIC Pn (filled squares) and MOS 1&2 CCDs (open circles). The solid line shows the best fit with two BB components to the total spectrum (all phases); the broken orange line shows the contribution from the soft component ($kT = 0.83$ keV) and the dotted blue line the hot component ($kT = 1.87$ keV). Panel B: Fits with two BB components with the same $kT$ values to the spectrum of only the pulsed emission, see text. Panel C: The same for the unpulsed/steady emission. In this case the evidence for the hot component is marginal. Error bars are 1σ.

Table 7. Spectral parameters for single or double black-body (BB) model fits to pulsed and unpulsed emission from PSR B1822−09 compared to the fit parameters for the double-BB fit to the phase integrated [0,1] total emission (2nd column), the same as the last column in Table 6; 3rd−5th columns, for only the pulsed emission; 6th, 7th columns, for the unpulsed emission. The complementary pulsed and unpulsed emission spectra are simultaneously determined in a Maximum Likelihood analysis in the 3D data space with axes the sky coordinates and pulsar phase (see text). Bold values indicate the $N_H$ and $kT$ values fixed to the best-fit values for the phase-integrated total emission. Fits are made over the energy range 0.2-10 keV using Pn and MOS 1&2 data of the observations listed in Table 3.

<table>
<thead>
<tr>
<th>Model</th>
<th>BB+BB Total</th>
<th>BB Pulsed</th>
<th>BB+BB Pulsed</th>
<th>BB+BB Unpulsed</th>
<th>BB Unpulsed</th>
<th>BB+BB Unpulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H \times 10^{-21}$</td>
<td>$2.40^{+0.43}_{-0.41}$</td>
<td>$2.40$</td>
<td>$2.40$</td>
<td>$2.40$</td>
<td>$2.40$</td>
<td>$2.40$</td>
</tr>
<tr>
<td>$\alpha_{BB1}$</td>
<td>$0.43^{+0.18}_{-0.14}$</td>
<td>$0.034^{+0.164}_{-0.026}$</td>
<td>$0.068^{+0.015}_{-0.014}$</td>
<td>$0.39^{+0.13}_{-0.10}$</td>
<td>$0.39 \pm 0.02$</td>
<td></td>
</tr>
<tr>
<td>$kT_1$</td>
<td>$0.083 \pm 0.004$</td>
<td>$0.095^{+0.025}_{-0.021}$</td>
<td>$0.083$</td>
<td>$0.083 \pm 0.003$</td>
<td>$0.083$</td>
<td></td>
</tr>
<tr>
<td>$R_{BB1}$</td>
<td>$2039 \pm 380$</td>
<td>$573^{+1382}_{-219}$</td>
<td>$811 \pm 89$</td>
<td>$1940 \pm 290$</td>
<td>$1940 \pm 290$</td>
<td></td>
</tr>
<tr>
<td>$F_{BB1} \times 10^{14}$</td>
<td>$3.2 \pm 0.2$</td>
<td>$0.75 \pm 0.22$</td>
<td>$0.46^{+0.10}_{-0.09}$</td>
<td>$2.70 \pm 0.14$</td>
<td>$2.64^{+0.15}_{-0.13}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{BB2} \times 10^{4}$</td>
<td>$10^{+12}_{-5}$</td>
<td>$6.8^{+39}_{-25}$</td>
<td>$7.2^{+19}_{-5.3}$</td>
<td>$7.3^{+0.9}_{-1.0}$</td>
<td>$2.1 \pm 1.0$</td>
<td></td>
</tr>
<tr>
<td>$kT_2$</td>
<td>$0.187^{+0.026}_{-0.023}$</td>
<td>$0.136^{+0.010}_{-0.009}$</td>
<td>$0.181^{+0.050}_{-0.035}$</td>
<td>$0.187$</td>
<td>$0.187$</td>
<td></td>
</tr>
<tr>
<td>$R_{BB2}$</td>
<td>$98^{+60}_{-25}$</td>
<td>$256^{+73}_{-47}$</td>
<td>$83^{+130}_{-31}$</td>
<td>$84 \pm 5$</td>
<td>$45 \pm 11$</td>
<td></td>
</tr>
<tr>
<td>$F_{BB2} \times 10^{14}$</td>
<td>$0.65 \pm 0.11$</td>
<td>$1.12 \pm 0.11$</td>
<td>$0.44 \pm 0.15$</td>
<td>$0.62^{+0.08}_{-0.08}$</td>
<td>$0.18 \pm 0.09$</td>
<td></td>
</tr>
<tr>
<td>$\chi^2 , / , \text{dof}$</td>
<td>$1.14 / 33-5$</td>
<td>$1.37 / 9-2$</td>
<td>$1.44 / 9-4$</td>
<td>$1.42 / 9-2$</td>
<td>$2.06 / 9-2$</td>
<td>$1.81 / 9-2$</td>
</tr>
</tbody>
</table>

Units: $N_H$ in cm$^{-2}$; $kT$ in keV; $\alpha_{BB}$ in ph/(cm$^2$s)keV$^3$; $R_{BB}$ in meter adopting a source distance of 1 kpc; Fluxes are unabsorbed for the 0.5-2 keV band in erg/(cm$^2$s).
this provides evidence for a relationship between the duration of its modes and a known underlying modulation timescale of the radio intensities within the modes.

- In the X-ray spatial analysis PSR B1822−09 was detected together with a nearby hard-spectrum X-ray source located at only $(5.1 \pm 0.5)''$ from the X-ray position of PSR B1822−09 ($\alpha_{2000} = 18^h 25^m 30^s 726.2, \delta_{2000} = -9^\circ 35' 23'' 14$). The new source dominates over PSR B1822−09 in skymaps for energies above 1.4 keV, and might be a PWN.
- The observations revealed X-ray pulsations from PSR B1822−09 between 0.4 and 1.4 keV with a broad sinusoidal pulse detected at a significance of 9.6σ. The X-ray profile reaches its maximum at phase $0.094 \pm 0.017$, slightly lagging the radio main pulse that peaks at phase 0, and is shifted in the opposite direction w.r.t. the position of the radio precursor at phase $-0.042$ (or 0.958).
- The X-ray phase distribution does not show an X-ray pulse at the phase of the radio interpulse, shifted by $180^\circ$ w.r.t. the phase of the main pulse. If PSR B1822−09 emits an X-ray pulse at the phase of the interpulse, weaker than the X-ray pulse at the phase of the radio main pulse, but with similar sinusoidal shape, then we do not expect to see this pulse above an unpulsed level that is created by the sum of the X-ray interpulse and the same flux from the X-ray main pulse.
- The pulsed fraction varies with energy from $\sim 0.15$ around 0.3 keV to a value of $\sim 0.6$ around 1 keV, indicative for a significant spectral difference between the pulsed and unpulsed emissions.
- The observations did not reveal evidence for simultaneous mode switching in the X-ray and radio bands, nor in the X-ray pulsed emission (pulse shape or flux), nor in the flux of the unpulsed X-ray emission. The total count rate for energies $0.4 - 1.4$ keV in the Q mode, $(1.32 \pm 0.05) \times 10^{-2}$, equals the count rate in the B mode, $(1.26 \pm 0.06) \times 10^{-2}$.
- There is no evidence for a relationship between the X-ray count rate and the underlying modulation timescale $P_3$ of the radio intensities within the modes. X-ray count rates for apparent different structures/components in the histograms of the radio Q-mode and B-mode lengths rendered the same count rates as obtained for the total Q and B mode.
- The total X-ray spectrum is well described by a double blackbody model with a cool component with $kT = 0.083 \pm 0.004$ keV or $T = 0.96 \pm 0.05 \, $MK and a hot component with $kT = 0.187 \pm 0.026$ keV or $T = 2.17 \pm 0.30 \, $MK. The first has a hot-spot radius of $2.0 \pm 0.4$ km and the latter $98.7_{-28}^{+48}$ m.
- The spectrum of the pulsed emission is well fit with a single blackbody, or a double blackbody with temperatures which are consistent with the values obtained for the hot and cool components in the spectrum of the total emission. For the latter fit, the flux of the hot component ($kT \sim 0.187$ keV with hot-spot radius of $\sim 84$ m) is consistent with the flux of the same component in the total-emission spectrum.
- The spectrum of the complementary unpulsed emission is almost entirely explained by the cool BB component with $kT = 0.083$ keV and hot-spot radius of $\sim 2000$ m. This fit can be somewhat improved by adding a small contribution of the hot component identified in the total spectrum.

9 DISCUSSION

To date, long simultaneous X-ray and radio campaigns on mode-switching pulsars have only been performed on PSR B0943+10 and PSR B1822−09. For PSR B0943+10, Hermsen et al. (2013) discovered simultaneous mode switching in X-ray and radio emissions, not seen in our campaign on PSR B1822−09. What causes the simultaneous mode switching is still an enigma. For PSR B0943+10, and now also for PSR B1822−09, the pulsed X-ray signals were detected for the first time, and the X-ray pulse profiles are similar; both exhibit a single sinusoidal pulse on top of unpulsed emission from the pulsars. This seems remarkable, because PSR B0943+10 is reported to be a nearly-aligned rotator with our line of sight passing near the pole (Deshpande & Rankin 2001). Therefore, we continuously view isotropic thermal emission from one single pole of this pulsar, and no pulsation of thermal emission is expected. For PSR B1822−09 we conclude in the Appendix that the existing evidence of the known radio characteristics of PSR B1822−09 strongly suggests this pulsar as having an orthogonal rotator geometry with our line of sight close to the equator. In this case we view such thermal emission from hot spots on both poles every rotation. Further in the discussion we will address similarities of, and differences between these two pulsars where appropriate.

9.1 The nature of the radio modes

The contrast between the two radio modes of PSR B1822−09 could hardly be greater, going well beyond their original nomenclature of B ("bright") and Q ("quiet"): in Fig. 2 the precursor (the best mode indicator and used here to define the mode) can be seen to sharply switch on and off in tandem with the intensity of the main pulse and in anti-correlation with the interpulse strength. Given the clear switch in X-ray emission found between the similarly-named modes of PSR B0943+10, one might expect the same effect in PSR B1822−09.

However, we report here that no radio vs X-ray correlation has been found (a 15% change in X-ray count rate could have been detected at an $\approx 3\sigma$ level), and it is interesting to consider how PSR B1822−09 differs from PSR B0943+10. The most obvious difference is that the magnetic axis of PSR B1822−09 is almost certainly highly inclined to its rotational axis (see Appendix), while PSR B0943+10 is in near alignment. Another difference lies in the nature of the modal modulations found in both pulsars. In PSR B0943+10 the B-mode exhibits a highly regular and rapid ($\sim 2P_3$) periodicity which may last for several hours, while in the Q-mode this modulation vanishes and is replaced by highly disordered emission. The conventional interpretation of this is that a precisely circulating carousel on the polar cap dissolves and is replaced by chaotic discharging until the order is suddenly recovered. Thus the mode lengths far exceed the subpulse modulation timescale.

In contrast, PSR B1822−09 has been found to have modulation in both modes, both on a much longer timescale ($\sim 46.6P_3$ and $70P_3$) than that of PSR B0943+10 and, significantly, not showing any subpulse “drift” found in carousel-driven modulation (not for orthogonal rotators though). The modulated emission is diffuse against a steady background (and often hard to discern). This suggests a different physical mechanism and the fact that both the mode change and the modulations occur simultaneously at both poles suggests that both reflect magnetospheric effects, rather than local polar cap physics.

In light of this it is perhaps not surprising that we find a link between mode lengths and modulation periods in PSR B1822−09. In Fig. 4(upper) we see that the most likely Q-mode length is just the Q-mode modulation period ($46.5P_3$) and in Fig. 4(lower) that
the most likely B-mode lengths are double and quadruple multiples of the B-mode modulation ($70P$). The further fact that the modulation periods of the two modes are harmonically related and that the modes probably (though this is unproven) start at the same phase of their modulations (either peak or trough) suggests that the modes may both be manifestations of a common underlying magnetospheric “clock”, possibly set by the inclination of the pulsar, the size of its light cylinder and its magnetic field strength.

This view has the advantage of divorcing the radio emission from polar cap conditions and suggesting a commonality to both modes, so that the uncorrelated thermal X-ray emission may indeed relate to an unchanging polar cap temperature. It is interesting to note that the two radio-detected pulsars of the “Three Musketeers”4 (PSR B0656+14 and PSR B1055–52) exhibit non-drifting modulations with timescales of $20P$. In the case of PSR B0656+14, Wetttevede et al. (2006, 2012) identify two distinct kinds of polar cap radio emission, of which only the “spiky” emission is modulated. It would be of interest to investigate this in further single-pulse studies of PSR B1822–09. The modulated and unmodulated radio emission could be identified with the two distinct pulsed black-body components already inferred for the X-ray emissions of PSR B0656+14, PSR B1055-52 and Geminga by De Luca et al. (2005) and proposed here for PSR B1822–09.

9.2 PSR B1822–09, a middle-aged pulsar like the Three Musketeers?

The total emission spectrum of PSR B1822–09 was well described by the sum of a hot BB and a cool BB spectrum. This differs from our findings for PSR B0943+10. In that case the total emission spectrum appeared to be the sum of a hot BB and a power-law spectrum. PSR B0943+10 has a long spin period of 1.1 s and is relatively old (5 Myr) compared to PSR B1822−09 which has a shorter period of 0.77 s and is younger (233 kyr). Also, the spin-down luminosity of PSR B1822–09 is a factor $\sim 40 (4.6 \times 10^{33}$ erg s$^{-1}$) larger than that of PSR B0943+10. The characteristics of PSR B1822–09 might better be compared with those of the Three Musketeers. These pulsars have similar characteristic ages, but rotate a factor 2-4 faster with spin-down luminosities up to a factor $\sim 8$ larger than PSR B1822–09. The Three Musketeers exhibit in the 0.2-8 keV band spectra with three components: a cool BB ($T=0.50-0.79$ MK), a hot BB ($T=1.25-1.90$ MK) plus a PL component that contributes negligibly below $\sim 2$ keV and dominates above (see De Luca et al. (2005)). The two BB components of PSR B1822–09 have temperatures only slightly higher than those of the Three Musketeers and the fluxes of their PL components are too low for detection when scaled to the an-order-of-magnitude lower count rate from PSR B1822–09.

The Three Musketeers have also been detected at high-energy gamma rays above 100 MeV, requiring a very hard steepening PL spectrum above the X-ray band in order to bridge several decades in luminosity to the high-energy gamma-ray band. Given the resemblance with PSR B1822–09 in the X-ray band, we selected all Fermi-LAT Pass 8-event data collected between August 4, 2008 and December 9, 2015 (MJD 54682.897 – 57365.907) with PSR B1822–09 in the field-of-view (region-of-interest: circular aperture of radius 5° centered on the pulsar), and extended the Jodrell Bank ephemeris to cover this time window. Using Fermi Science Tools5 getselect and gtbaray, respectively, we further selected only events with Evclass = 128, evttype = 3 and Earth zenith angle $< 105^\circ$, and barycentered the event arrival times using the Solar System Ephemeris file DE200. We selected events with energies above 300 MeV, because we expect rather hard gamma-

4 Becker & Trümper (1997) dubbed PSR B0656+14, PSR B1055–52 and Geminga / PSR J0633+1746 the Three Musketeers. These three middle-aged pulsars have similar characteristics and were the only pulsars in the first list of 27 X-ray detected pulsars that exhibited thermal X-ray components (then probably also by the Vela pulsar), which could be attributed to thermal emission from the neutron star stellar surface; so called cooling neutron stars.

5 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
ray emission from middle-aged pulsars. Namely, Posselt, Spence & Pavlov (2015) list the 11 nearby middle-aged pulsars detected by the LAT. They have power-law spectra with average index of \( \sim -1.1 \) and average exponential cutoff of \( \sim 1.3 \) GeV. We phase folded the barycentered arrival times of events that were detected from within an energy-dependent aperture around PSR B1822−09 that contains \( \sim 68\% \) of the point-source counts (\( \theta_{68\%} \) [degree] = \( 0.8\times (E[\text{MeV}]/1000)^{0.75} \)) (Abdo et al. 2009). We verified that for the energy range where we might expect to detect events from PSR B1822−09 (up to a few GeV) this parametrisation is consistent with the most recent one derived for Pass 8-event data\(^6\). The obtained pulse profile is shown in the bottom panel of Fig. 12. There is an indication for the detection of a pulsed signal at a significance level of \( \sim 2.7\sigma \) (Buccheri et al. 1983, \( Z^2 \) value), or a 0.60% chance probability. Fig. 12 shows the gamma-ray profile in comparison with those in the radio band for the Q and B mode and the X-ray profile. It is interesting to note that the maximum of the broad gamma-ray profile at phase 0.92 ± 0.05 approximately coincides in phase with the PC in the radio B mode, and is shifted by 3.3 \( \sigma \) with respect to the maximum of the X-ray pulse at phase 1.094 ± 0.017. We note, that the Fermi-LAT Third Source Catalog (Acero et al. 2015) does not report a source within a distance of a degree of PSR B1822−09.

9.3 Modelling of the pulsed fraction

The apparently (nearly) orthogonal rotator geometry of PSR B1822−09 seems difficult to reconcile with the energy dependence of the pulsed fraction, reaching a maximum value of \( \sim 0.6 \) at 1 keV, for a single hot (\( T = 2.17 \pm 0.30 \) MK) pulse on top of cool (\( T = 0.96 \pm 0.05 \) MK) unpulsed emission. In fact, we derived from the spectral analysis that the hot pulsed component has a pulsed fraction that could be as high as 100%.

For an orthogonal-rotator geometry it is remarkable that we did not see evidence for an X-ray pulse in the pulse profile from the phase of the IP. However, as we discussed, such a pulse can be hidden in the pulse profile in a flat unpulsed emission level when the X-ray MP and IP both are sinusoidal. The fit with two BBs to the spectrum of the unpulsed emission gives a hint for the presence of a weak hot component. If this hot component in the unpulsed emission is genuine, then in first approximation \( \sim 50\% \) can be assigned to the MP and \( \sim 50\% \) to the IP (assuming both have a sinusoidal shape). The best-fit flux values then suggest an IP flux of \( \sim 12\% \) of that of the MP and a pulsed fraction of just the hot component of \( \sim 0.8 \). These high pulsed fractions cannot be produced by isotropic blackbody emission in hot spots with the same temperatures and areas on both poles for the geometry assigned to PSR B1822−09.

When we take the approximate relation \( F_{\text{BB}} \propto T^4 \) then the temperature of the antipodal spot (for the same area) should by \( \sim 50\% \) of that of the hot spot producing the main X-ray pulse to reach a pulsed fraction of \( \sim 0.8 \). This would mean a temperature of \( \sim 0.110 \) keV.

For PSR B0943+10 we obtained similarly high pulsed fractions (Hermsen et al. 2013), namely, the pulsed fraction in the Q mode of a single hot thermal pulse on top of non-thermal unpulsed emission increased from \( \sim 0.2 \) at 0.2 keV up to \( \sim 0.6 \) at 1 keV. Considering just the thermal pulsed component in the Q mode, the modulation was also reported to be consistent with 100%. These pulsed fractions are confirmed in the longer follow-up campaign on this pulsar (Mereghetti et al. 2016). PSR B0943+10 has an estimated magnetic field strength at the pole of \( 2 \times 10^{12} \) G, significantly above a field strength of \( B = 10^{11}(E/1\text{keV}) \) G, when the electron cyclotron energy \( E_c \) exceeds the photon energy, and magnetic beaming makes the local emission essentially anisotropic (beamed along the direction of the magnetic field). The properties of a neutron star atmosphere (e.g. fully or partially ionised) determine the angular distribution and shape of the pulsations. The geometry and viewing angles determine finally what we observe. For example, Pavlov et al. (1994) showed that for a fully ionised neutron star atmosphere a strong narrow pencil beam along the magnetic field direction can be expected together with a broad fanlike component across the magnetic field. Even in the case of a uniformly heated neutron star surface the angular distribution is beamed along the magnetic axis (Zavlin & Pavlov 2002). More recently, van Adelsberg & Lai (2006) also considered atmosphere models of magnetized neutron stars, and calculated characteristic beaming patterns exhibiting a thin pencil beam at low emission angles and a broad fan beam at large emission angles. See also similar work by Zane & Turolla (2006) and Turolla & Nobili (2013). Stimulated by the discovery of simultaneous X-ray radio mode switching (Hermsen et al. 2013), Storch et al. (2014) considered a magnetized partially ionized hydrogen atmosphere model to explain the high pulsed fractions in the Q mode of PSR B0943+10, while remaining consistent with the nearly aligned dipole field geometry (Deshpande & Rankin 2001), and using the magnetic field strength of \( 2 \times 10^{12} \) G inferred from its \( P \) and \( \dot{P} \). They derived pulsed fractions ranging from 0.4 at 0.2 keV, up to a maximum of 0.9 at a few keV, that are higher than the pulsed fractions of the total emission. However, their calculations assumed just a single standard polar cap hot spot, and do compare well with, or are somewhat lower than, the measured values for the total emission when the calculated pulsed fractions are corrected (lowered) for the underlying unpulsed emission (see also Mereghetti et al. 2016).

PSR B1822−09 has an even stronger estimated magnetic field strength of \( 6.4 \times 10^{12} \) G such that also for this pulsar magnetic beaming can shape the measured pulse profile. For its orthogonal geometry, we obviously need strong beaming effects such that hot X-ray emission from the IP is totally or mostly beamed away from our line-of-sight, while the X-ray emission from the MP passes through our line-of-sight. The cool unpulsed component in the total emission from PSR B1822−09, originating from an area with large radius of \( \sim 2 \) km, can be explained as the sum of broad pulses from both poles, possibly in fan beams. This would explain the finding that the estimated radius is significantly smaller than one expects for cool emission originating on the entire surface of the neutron star. This is in contrast to the cool areas found for e.g. the Three Musketeers, that are (more than) an order of magnitude larger, and their cool emission is thought to originate from the entire surface.

Following the above argumentation, if the thermal X-ray emissions from PSR B0943+10 and PSR B1822−09 are strongly beamed, and mode switching is due to some change in structure of the magnetic field, then for PSR B1822−09 the beaming angle of the X-ray pulsations might change less w.r.t. our line of sight between the B and Q mode than in a mode switch of PSR B0943+10.

The lack of observable change in the pulse shape and brightness of PSR B1822−09 can then just be a coincidence of viewing geometry.
9.4 Conditions at the inner acceleration region

It is believed that the hot spots are actual polar caps heated by backstreaming ultra-relativistic particles accelerated in the inner acceleration region. Thus, the study of properties of hot spot components, such as size and temperature, can provide valuable information about this region of a neutron star. One can use the magnetic flux conservation law to estimate the magnetic field at the polar cap region \( B_p = B_{dp} R_{dp}^2 / R_{dp}^2 \). Here, \( B_{dp} \) is the dipolar component of the magnetic field at the polar cap, and \( R_{dp} \) is the radius given by the last open field line of the dipolar magnetic field component. Old pulsars with their spectrum dominated by hot spot radiation show that an actual polar cap is considerably smaller than \( R_{dp} \), see e.g. PSR J0108−1431 (Pavlov et al. 2009; Posselt et al. 2012), PSR J0633+1746 (Kargaltsev et al. 2005), PSR B1929+10 (Mislanovic, Pavlov & Garmire 2008). Furthermore, the estimated magnetic field strengths at the polar cap for these pulsars (\( B_p \approx 10^{14} \text{G} \)) and temperatures of a few million Kelvin satisfy the condition for the formation of a Partially Screened Gap (PSG) (see Gil et al. 2003; Medin & Lai 2007). Although, the fitted hot spot radius of PSR B1822−09 \((R_{Hs} \approx 100 \text{ m})\) is smaller than the conventional polar cap size \((R_{dp} = 165 \text{ m})\) the derived magnetic field strength at the polar cap \( B_p = 2.7 \times 10^{13} \text{G} \) and the fitted temperature \( T_p \approx 2.2 \times 10^6 \text{ K} \) do not satisfy the condition for PSG formation (see Eq. 5 in Szary, Melikidze & Gil 2015). For such a high surface temperature and relatively weak surface magnetic field the outflow of thermal ions from the surface screens the gap completely. It is worth noting that both the size and temperature of the hot spot depend on the considered model. The atmospheric models, suggested by the high pulsed fraction, could result in different properties of the polar cap, and thereby different conditions in the inner acceleration region. But, an alternative acceleration mechanism might be at work, for instance the space-charged-limited flow model (Arons & Scharlemann 1979; Harding, Muslimov & Zhang 2002). In that case, surface charges can freely flow into the magnetosphere and the inner gap is thought to be space-charge limited. Pairs are created higher up in the magnetosphere near the so-called “pair-creation front”. Harding & Muslimov (2001) discuss pulsar polar cap heating and surface thermal X-ray emission in the case of Curvature Radiation pair fronts, and Harding & Muslimov (2002) in a second paper the case of Inverse Compton Radiation pair fronts. For the age and temperature of PSR B1822−09 only the first scenario might explain our measured thermal X-ray luminosity.

10 CONCLUSIONS

We have observed PSR B1822−09 for \( \approx 55 \) hours simultaneously at X-ray and radio frequencies. The X-ray results reveal a single-peaked, thermal sinusoidal pulse combining a small pulsed hot spot together with a 2km-wide cooler region. Had we observed the pulsar at X-rays alone we might have concluded it was a middle-aged Geminga-like pulsar at low/intermediate inclination so that only a single polar hot spot is visible to us. This result was totally unexpected since it is known that at radio frequencies this pulsar displays an interpulse, and there is evidence from the polarisation that its magnetic axis is highly inclined to the rotation axis – so why doesn’t the X-ray emission have a double peak? We argued that a weak broad pulse could be hiding in the unpulsed emission.

A second puzzle arises from the lack of modulation in the X-ray pulse. For many years it has been known that PSR B1822−09 switches in the radio band between two very distinctive modes of emission centred on the magnetic polar regions on a timescale of several minutes. During our observations we collected the largest ever number of mode transitions, and so for the first time we were able to build an overview of the statistics of the mode switches. These suggest a complex relationship between the durations of the modes and independently-reported modulation timescales present within each mode. Following the example of PSR B0943+10, where the pulsed and unpulsed X-ray emissions in its two radio modes differ in flux by a factor \( \sim 2 \) and the polar hot-spot temperature seems to switch between two values (Mereghetti et al. 2016), one might expect a detectable modulated response also in the X-ray emission of PSR B1822−09. However, despite multiple attempts at matching our X-ray counts with aspects of the radio modulations, we found no correlation between the X-ray emission and simultaneously observed radio emission mode, e.g. the total count rates in the two modes are within \( \sim 5\% \) \((1\sigma)\) the same. At face value, it seems that all the X-ray and radio emission of PSR B1822−09 have in common is the same rotation period and the same phase longitude for the main pulse.

Interpreting the X-ray observations of PSR B1822−09 we conclude that the X-ray emission may consist of emission from a principal small hot spot at the main pulse and two broader and cooler hot spots at the main pulse and interpulse phase, the first being \( \sim 35\% \) stronger than the latter. This may be explained by exploiting the effects of photon beaming in a strong magnetic field, with the hot X-ray interpulse not being directed towards us. In this context it may be worth remembering that the radio MIP/IP ratio is \((\sim)\) quite extreme \((\text{see Fig. 12})\). Nevertheless, the puzzle remains as to why there appears to be no correlation between the thermal emission of the X-rays and the dramatic pan-magnetospheric mode changes implied by the radio emission. This outcome therefore forms an extreme contrast to the equivalent observations of the likely near-aligned pulsar PSR B0943+10 (Hersmen et al. 2013; Mereghetti et al. 2016).

One way out of this dilemma may be to argue that while the thermal X-rays come from the neutron star surface, the radio emission may originate from magnetospheric effects which do not directly impact the star’s polar caps or its wider surface. The polar interplay of the B and Q modes gives little doubt that some form of communication exists between the poles, and this must take place within the supposedly closed magnetosphere. Furthermore, it can be shown that the PSG (partly screened gap) mechanism for the production of polar gap patterns immediately above the surface will probably not work given the weak inferred magnetic field strength of PSR B1822−09. So an alternative mechanism, presumably operating at higher altitudes in the magnetosphere, must be responsible for the radio emission. Nevertheless, we still have to explain how the pulsar’s apparently unmodulated hot-spot surface temperatures can be maintained at such high levels.

Finally, following the findings of Lyne et al. (2010) that PSR B1822−09 is one of a number of pulsars whose long-term profile modulations can be linked to changes in spin-down rates, it seems we must now come to the unexpected result that this pulsar’s thermal X-rays do not, or hardly, participate in the spin-down mechanism.

The results of our campaign on PSR B1822−09 have therefore raised more questions than answers. There is a clear disconnect between the radio and X-ray emission of this pulsar, and at times it has felt as though we are observing two different pulsars with the same period. One conclusion is certain: we are still far from understanding either the radio or the X-ray production mechanisms of pulsars.
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**APPENDIX A:** THE GEOMETRY OF PSR B1822–09

PSR B1822–09 exhibits two distinct emission modes. In its ‘B’right mode it shows a main pulse (MP) along with a precursor component (PC), and in its ‘Q’ uiet mode one sees a weaker and more complex MP along with an interpulse (IP). This IP is separated by almost exactly 180° (see Backus, Mitra & Rankin 2010), hereafter BMR10, although strangely the MP and IP show correlated intensity fluctuations while in principal they should have independent emission characteristics (Fowler, Morris & Wright 1981; Fowler & Wright 1982; Dyks, Zhang & Gil 2005; Gil et al. 1994). It is however this 180° separation seen in the Q-mode between the MP and IP which leads one to conjecture that the pulsar might be an orthogonal rotator (e.g. Hankins & Fowler 1986; Dyks, Zhang & Gil 2005, hereafter DZG05, BMR10). Although two further checks are necessary to strengthen the orthogonal rotator argument: the first is that the 180° separation between the MP and IP is seen over the entire band of observable frequencies, and the second is that the linear polarization position angle (PPA) traverse should be adequate described by the rotating vector model (RVM). Unfortunately no exhaustive study of these effects exists in the literature, possibly due to the lack of high-quality single-pulse observations permitting separation and individual study of the B and Q modes7.

As pointed out by DZG05 the 180° MP-IP separation can also be explained in almost aligned rotator models where the MP and IP are produced by the line of sight cutting through two sides of the hollow conical emission beam. However in this case, due to radius to frequency mapping one expects to see the MP-IP separation evolving with frequency. The other alternative in the aligned rotator category is a single-pole model, wherein the line of sight always remains within the emission cone and under special situations emission components separated by 180° are seen. Although in these cases (often known as wide profile pulsars) a low level bridge of emission is expected between the profile components, which however is completely absent in PSR B1822–09.

**A1 Fitting the RVM**

We are in possession of the high quality polarized single pulse P-band GMRT observation that was used by BMR10. Here we use this observation to explore whether the PPA traverse can successfully be fitted by the rotating-vector model (RVM). The top-left panel of Figure A1 shows the single-pulse sequence of 2077 pulses while the top-right panel shows the PPA histogram (as a gray scale in the bottom panel) for these pulses. Only those PPAs are shown in the histogram where the single pulse linear polarization power exceeds five times the rms noise level. The red points with error bars show the average PPA traverse. It is clear from this plot that the single pulse linear polarized power is strong for the MP and the PC, but weak for the IP. The bottom left and right plots show the PC and MP regions of the PPA histogram for the B and Q mode respectively. Qualitatively, the PPA behavior for these two modes is seen to be similar; it is the PPA distributions within the two modes that changes.

Fitting the RVM to these PPA traverses is definitely a challenge. The original version of the RVM introduced by Radhakrishnan & Cooke (1969) was advanced by Blaskiewicz, Cordes & Wasserman (1991, hereafter BCW) where the first-order special relativistic effects of aberration and retardation (A/R) were included. In the most general case, the RVM depends on 5 parameters namely α the angle between the rotation and dipolar magnetic axes, β the impact angle between the magnetic axis and the observer’s line of sight, the distance r_em from the center of the neutron star, the fiducial phase ψ_0, and the arbitrary shift of the PPA at the fiducial phase ψ_u.

\[
\psi = \psi_0 + \tan^{-1} \left( \frac{\sin(\alpha)\sin(\phi - \phi_u)}{\sin(\eta)\cos(\alpha) - \sin(\alpha)\cos(\phi - \phi_u)} \right)
\]  

(A1)

Here \( \eta = \alpha + \beta, \psi \) is the PPA, \( \alpha \) is the pulsar phase, \( P \) the pulsar period and \( c \) the velocity of light. The r_em term in the numerator is due to the A/R effects discussed by BCW, and for r_em = 0 the equation reduces to the usual RVM. For normal pulsars like PSR B1822–09 it is well known that the radio emission originates typically at an altitude of about 1%-5% of the light-cylinder radius, and the effect of A/R is to simply shift the PPA both in \( \psi \) and \( \phi \), keeping the functional form of the traverse similar. For the RVM fitting exercise below we will hence keep r_em ~ 500 km such that the quantity \( (6\pi/P)(r_{em}/c) \sim 0.04 \), where \( P = 0.769 \) sec. The usual strategy for fitting Eqn. A1 is to guess values for \( \phi_u \) and \( \psi_u \), based on the PPA traverse, and search for the parameters \( \alpha \) and \( \beta \). Unfortunately, for a given set of \( \alpha \) and \( \beta \) the RVM can only be distinguished at the wings of the main pulse provided the width of the MP exceeds typically beyond 30°. Certainly this is not the case for PSR B1822–09, where the MP is only about 12° wide. This essentially means that fitting the RVM will not yield meaningful constrains on \( \alpha \) and \( \beta \).

7 Note that the recent PhD thesis of Phrudth Jaroenjittichai, https://www.escholar.manchester.ac.uk/uk-ac-man-scw:199950, University of Manchester, dedicates a chapter to the study of PSR B1822–09.
Let us illustrate the above point by doing the fits. We first choose the Q-mode profile where the effect of the PC is low and the MP is prominent. At this stage we should ask why the PC is not included in the RVM fits, and the reason is that the PC observed in several pulsars appears to be a different emission component with no clear polarizational relationship to that of the MP. The shape of pulse profiles can usually be explained by the core-cone model where a central core emission component is surrounded by pairs of nested conal features. Cones are of two types, outer and inner. Outer cones show radius-to-frequency mapping (RFM), whereas the inner cones evolve with frequency much less than do outer cones. In a detailed study of pulsars with PC components by Basu, Mitra & Rankin (2015), the authors demonstrated that the location of the PC components w.r.t. the MP remain constant with frequency, whereas the components in the MP usually show the expected radius to frequency mapping. For PSR B1822–09 the PC-MP separation (estimated as the peak of the PC and that of the MP) is about 14.3° over the band from 243 MHz to 10.3 GHz, whereas the width (estimated using half power point) of the MP evolves from 8.1° to 3.6° over this frequency range (see their Fig 1. and Table 2). Constancy of width with frequency is also a known property of inner cones within the core-cone model (Mitra & Rankin 2002). (PSR B1822–09’s leading PC component might be modeled as an outer cone where the usual trailing component is not seen; however, its lack of evolution with frequency strongly mitigates against this explanation.) The MP on the other hand can be classified as a triple under the core-cone model showing the usual inner cone lack of RFM. We will also not include the IP for fitting the RVM. There are several reasons for doing so, but the most important one is that the sensitivity of our data does not allow us to interpret the PPA traverse by disentangling its Orthogonal Polarization Mode behaviour.

Returning to fitting the RVM to the MP emission, we need to provide initial values for $\phi_0$ and $\psi_0$. We assign $\phi_0$ (and read off the corresponding $\phi_0$ value) as the phase corresponding to the peak of the Q-mode profile, which is also the peak of the central core component of the triple profile classified by BMR10. The PPA traverse at this phase shows an orthogonal jump, which is also characteristic of core emission. With these values a grid search was carried out...
Figure A2. The $\chi^2$ contours are shown of fitting the RVM for various values of $\alpha$ along the x-axis and $\beta$ along the y-axis. Clearly the $\chi^2$ minimum is unconstrained. The curves represent multiples of the minimum $\chi^2$ as 2 (green), 3 (red), 4 (blue), 5 (cyan), 6 (magenta) and 7 (yellow), 8 (orange), 9 (yellow-green), 10 (cyan-green).

to find $\alpha$ and $\beta$, and the $\chi^2$ contours are shown in Fig. A2. Clearly a wide range of $\alpha$ and $\beta$ values are consistent with the fits, as the parameters are correlated up to 99%. The left and right panels of Fig. A3 show the RVM solutions for orthogonal and aligned rotator cases, respectively, and these solutions cannot be distinguished (see captions for more details). Hence, RVM fits to the MP PPA traverse cannot constrain the geometry, in particular to distinguish between an orthogonal and aligned rotator.

If the IP could be included in the fits, there would be a possibility to distinguish between the aligned and orthogonal rotator geometries, since the PPA traverses are very different in the IP region as shown in Fig. A4. However, the lack of sufficiently sensitive single pulse polarization makes this task impossible for the moment.

A2 Geometry using core width

If a core component can be identified in a pulse profile, then Rankin (1990, 1993a,b) has shown that the half-width of the core component ($W_c$) can be related to $\alpha$ as $\sin(\alpha) = 2.45^5 P^{-0.5} / W_c$. Furthermore, using the steepest gradient point of the PPA traverse $R = \sin(\alpha) / \sin(\beta)$, $\beta$ can be found. Rankin (1993b) classifies the MP of PSR B1822–09 as having a core-cone configuration. Furthermore, her Table 5 gives a value of 2.8° for $W_c$, implying per the above relationship that $\alpha \sim 86^\circ$. Also a value of $R = 50$ (Lyne & Manchester 1988) has been used to get $\beta \sim 1.1^\circ$. From our analysis we confirm that $W_c \sim 2.8^\circ$, however based on our best RVM solutions we find a significantly smaller value for the steepest gradient—i.e. $R \sim 2.4$ giving $\beta \sim 16^\circ$. The unusually large $\beta$ value is however worrying, since it leads to an unusually large beam radius of about 16° and emission heights of about 1300 km. However one should realize that for this pulsar the PPA histograms do not constrain $R$ very well. It hence appears that the lack of a clean description of the RVM for PSR B1822–09 leads to an uncertain geometrical interpretation.

A3 Orthogonal Rotator

While the methods for determining $\alpha$ and $\beta$ largely fail for PSR B1822–09, there is striking evidence that the IP and the MP are separated by almost precisely 180° at 325 MHz (BMR10, Latham et al. 2012) and nearly that over a broad band (Hankins & Fowler 1986) – though it is important to restudy this separation on the basis of modern techniques. Furthermore, the narrowness of the MP core component is also strong evidence for an orthogonal alignment, the difficulty of determining $\beta$ notwithstanding. Most recently, Pilia et al. (2016) show in their Figure B.2 that 350 MHz and 1400 MHz profiles are very well aligned, appearing to be the strongest argument for an orthogonal rotator. Therefore, the existing evidence strongly points to PSR B1822–09 as having an orthogonal rotator geometry. Of course, this orthogonal geometry raises an urgent question about the origin of the modulational “cross-talk” observed between the pole and interpole of PSR B1822–09 and many more MP-IP pulsars (e.g. Weltevrede, Wright & Stappers 2007; Weltevrede, Wright & Johnston 2012).
Figure A3. The left and right panels show the RVM fits (as dashed magenta lines) where the left solution corresponds to an approximately orthogonal case with $\alpha = 84^\circ$ and $\beta = 16^\circ$ and the right solution corresponds to an almost aligned case with $\alpha = 7^\circ$ and $\beta = 1^\circ$. These two fits cannot be distinguished.

Figure A4. The left panel in this figure shows the full IP-MP RVM for the almost orthogonal rotator case using $\alpha = 84^\circ$ and $\beta = 16^\circ$. The right panel shows the full RVM for an almost aligned case using $\alpha = 7^\circ$ and $\beta = 1^\circ$. Note that in the IP region the two curves show very different behaviour. However since we cannot distinguish the OPM due to lack of sensitive data, we cannot trace the behaviour of the PPA traverse. The average PPA cannot be used for understanding the RVM.