Title: Synchronous X-ray and Radio Mode Switches: a Rapid Global Transformation of the Pulsar Magnetosphere

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Abstract: Pulsars emit low-frequency radio waves through to high-energy gamma-rays that are generated anywhere from the surface out to the edges of the magnetosphere. Detecting correlated mode changes in the multi-wavelength emission is therefore key to understanding the physical relationship between these emission sites. Through simultaneous observations, we have detected synchronous switching in the radio and X-ray emission properties of PSR B0943+10. When the pulsar is in a sustained radio 'bright' mode, the X-rays show only an un-pulsed, non-thermal component. Conversely, when the pulsar is in a radio 'quiet' mode, the X-ray luminosity more than doubles and a 100%-pulsed thermal component is observed along with the non-thermal component. This indicates rapid, global changes to the conditions in the magnetosphere, which challenge all proposed pulsar emission theories.

Main Text:
Radio pulsars are powered by the energy released as the highly magnetized neutron star spins down. The radio pulses are generated in the pulsar magnetosphere, most probably close to the neutron star surface (1,2). Shortly after the discovery of pulsars, it was observed that the radio pulse behavior can discretely change on timescales as short as a rotation period. These changes in emission mode can manifest as switches between ordered and disordered states or variations in intensity and pulse shape, including the complete cessation of observable radio emission (3,4).

Because the emitted radio luminosity is a negligible fraction of the available spin-down energy, usually substantially less than $10^{-3}$, this phenomenology was presumed to be related solely to microphysics of the radio emission mechanism itself. This perception has recently been challenged by the identification of a relationship between the spin properties of neutron stars and their radio emission modes. PSR B1931+24 was observed to cease emitting for tens of days, during which it spins down ~50% less rapidly (5). PSR J1841–0500 (6) and PSR J1832+0029 (7) exhibit similar behaviors. A number of other pulsars display smaller changes in spin-down rate, which correlate with variations in their average radio pulse shapes (8). The implication of these results is that mode changing 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. Whereas changes in spin-down rate can only be detected on time-scales of a few days or longer, the recently identified link with the rapid switching observed in radio emission modes suggests a transformation of the global magnetospheric state in less than a rotation period. Despite the recent flurry of pulsar detections at high energies (9), the only causal relation between the radio pulses and emission at other wavelengths, likely emanating from different locations in the
magnetosphere, has been made for optical emission and giant radio pulses from the Crab pulsar (10)

PSR B0943+10 is a paragon of mode-changing pulsars. Relatively old (characteristic age 5 Myr), with a long spin period (P = 1.1 s), it switches at intervals of several hours between a radio-bright, highly organized mode (B) and a quieter chaotic mode (Q) (11,12). At the B- to Q-mode transition a sub-pulse drifting structure dissolves within a few seconds, the emission becomes disorganized, and an additional highly polarized radio component appears, preceding the main pulse by 52° of pulse longitude (13). PSR B0943+10 has also been detected in two short observations with the XMM-Newton observatory as a weak X-ray source (14). Assuming the X-rays to be thermal, this was used to support a model in which one system of streaming particles produces both the sub-pulse-modulated radio emission directly, as well as thermal X-ray emission through bombardment of the polar cap surface (15). Because the particle streams are thought to be determined by the magnetosphere as a whole, detection of simultaneous X-ray/radio mode switching would uniquely probe the interaction between local and global electromagnetic behavior. Moreover, this would strengthen the earlier conclusion that entire magnetospheres change, settling down within a few seconds.

To test these hypotheses, we carried out a simultaneous X-ray/radio observing campaign on PSR B0943+10, between 4 November and 4 December 2011. These observations were designed to investigate what changes, if any, occurred in the X-rays when the radio emission changed mode. The X-ray observations consisted of six 6-hr observations in the 0.2 - 10 keV energy band with ESA’s XMM-Newton space observatory ((16), Table S1), accompanied by radio observations with the Indian Giant Metrewave Radio Telescope (GMRT) at 320 MHz and the international Low Frequency Array (LOFAR) at 140 MHz, both simultaneously.

To identify the radio B- and Q-mode time windows, the radio pulse sequences were folded with up-to-date ephemerides from the Jodrell Bank long-term timing program (17) (Fig. 1). We could determine the times of mode switches from GMRT and LOFAR data with an accuracy of a few seconds. Table S2 lists the used B- and Q-mode time windows, which completely cover our XMM-Newton observations. In the ~30 hrs of usable X-ray observations, PSR B0943+10 spent roughly equal amounts of time in the B- and Q-modes.

PSR B0943+10 was clearly detected in each of our XMM-Newton observations with the simultaneously used CCD detectors PN (18) and MOS-1+2 (19) of the European Photon Imaging Camera (EPIC). The derived count rates ranged from that of the previously reported value for the PN detector of (0.38 ± 0.07) x 10^{-2} counts/s (0.5-8 keV) (14) to about twice that value, providing evidence for X-ray variability in an old, rotation-powered pulsar. Dividing the 0.2-10 keV X-ray events into the radio-derived B- and Q-mode time windows, we found the X-ray count rate to be more than a factor of two higher in the radio Q-mode than in the B-mode (Fig. S1). In the B-mode, the PN CCDs had a count rate of (0.44 ± 0.07) x 10^{-2} counts/s, whereas in the Q-mode this more than doubled to (1.08 ± 0.08) x 10^{-2} counts/s. This was independently confirmed with the MOS detectors, providing evidence for simultaneous mode switching in the radio and X-ray properties.

To search for X-ray pulsations, we selected events in the PN/MOS-1+2 CCDs that arrived in the Q-mode time window and within a radius of 15 arcseconds from the source position. From this, we obtained a 6.6-σ detection of a pulsed signal (top panel of Fig. 2B) at a period
consistent with the rotational frequency predicted by the Jodrell Bank ephemeris (Table S3). The pulse profile (energies 0.5-2 keV) is broad. Surprisingly, the X-ray events detected during the radio B-mode do not show any evidence for a pulsed signal (top panel Fig. 2A). Figure 2 shows that the broad X-ray pulse in the Q-mode covers the phases of the main radio pulse and precursor; the latter is clearly visible in the Q-mode, 52° (0.14 phase) ahead of the main pulse at 320 MHz (Fig. 2B).

X-ray spectral analysis (16) reveals two components in the Q-mode. The best spectral fit to the total (i.e. pulsed and unpulsed) spectrum is the sum of a power-law and thermal black-body component (Fig. 3A with fit parameters in Tables 1 and S4). The spectrum of the pulsed component in the Q-mode is best described by a single thermal black-body model (Fig. 3B, Tables 1 and S4). It appears that the spectral fits to the thermal component in the total Q-mode spectrum and the thermal pulsed spectrum in the Q-mode are statistically consistent (Δ flux is 0.1 σ and ΔkT=2.5 σ). This means that the Q-mode total X-ray emission consists of an un-pulsed component with a steep, non-thermal power-law spectrum, and a ~100% pulsed component with a thermal black-body spectrum. This is also reflected in the variation of the pulsed fraction with energy (Table S5). In the B-mode, the spectrum can be satisfactorily described with a single power-law as well as a single black-body shape (Table S4). However, the most likely shape is a non-thermal spectrum (Fig. 3C), indistinguishable from the non-thermal component in the total Q-mode spectrum (supplementary online text).

PSR B0943+10 is one of just 10 old (characteristic age > 1Myr), non-recycled radio pulsars where X-ray emission has also been detected (20-22). Although the surfaces of such pulsars have cooled substantially since birth, the observed X-ray emission is argued to be thermal in some cases. This has led to the conclusion that such pulsars may have 'hotspots' on their magnetic polar caps, generated by the bombardment of particles accelerated in the radio emission process. In all models, the bombarding particles result from pair-creation in the pulsar magnetosphere. In polar-vacuum-gap models (1,23) this occurs directly above the surface. Recent adaptations of the model (15) predict the thermal X-ray brightness of pulsars that exhibit regular modulation of their radio sub-pulse drift. Such modulation is indeed observed in the B-mode of B0943+10 (24), and the original X-ray detection of this pulsar (14) appeared to support this prediction, if one assumes the X-rays have a thermal origin. However, while the reported count rate suggests that the pulsar was in the B-mode during those observations, our spectral analysis shows that the X-ray emission in the B-mode is actually non-thermal. Surprisingly, strong thermal X-rays are only detected in the Q-mode, where the observed radio emission is weak and chaotic.

Space-charge-limited-flow models (2) also feature pair-created particles that heat the polar cap via backflow. These differ from polar-gap models, however, in that charged primary particles are freely drawn from the neutron star surface. The thermal luminosities predicted for older pulsars (25) fall below what is observed in PSR B0943+10's Q-mode and below the model's expected non-thermal cascade emission, consisting of contributions from curvature radiation, inverse Compton scattering and synchrotron radiation (26). Such non-thermal emission, expected on open field-lines, would almost certainly be mode-dependent, in contrast to what we observe.

Modeling of PSR B0943+10’s geometry (27) strongly argues that the magnetic and spin axes are nearly aligned, with our line-of-sight passing near the pole (24) (Fig. 4). This implies that the isotropically emitted X-rays of a polar hotspot should appear un-modulated throughout
the rotation period, contrary to the observed Q-mode X-ray pulsations. One possible interpretation is then that the observed X-ray pulsations result from time-dependent scattering of the emission within the closed magnetosphere (Fig. 4), a scenario similar to that proposed to explain magnetospheric eclipses of pulsed radio emission in the double pulsar system PSR J0737–3039 (28,29). If so, then the observed thermal emission in the Q-mode is only about half the actual hotspot emission, doubling the inferred area of the hotspot.

If scattering plays an important role in the Q-mode, the absence of X-ray pulsations and thermal X-rays in the B-mode may be attributed to increased scattering. As suggested to explain nulling and mode switching in radio pulsars (30), an expansion in the volume of the closed magnetosphere might accompany the mode-change, though it is unlikely to achieve the required degree of screening. It thus appears that at B-mode onset the surface hotspot emission is reduced to undetectable levels within a few seconds, induced by a drastic reduction in the downward flow of charged particles.

In the context of the polar-gap model, it has been suggested (31) that mode changes occur when the local surface temperature crosses a critical value, ~10^6 K, that separates dominant emission mechanisms. This would require hotspots to be detectable in both modes, in contradiction with our results. B-mode emission may represent a cooler mode where curvature radiation dominates. However, the temperature transition remains unexplained and our results strongly suggest that a global, rather than local, mechanism is required. Indeed, for a near-aligned pulsar such as PSR B0943+10, a range of quasi-stable magnetospheric configurations is expected (32,33), and the non-linear system is proposed to suddenly switch between specific states, each having a specific emission beam and spin-down rate (30).

Whatever the true nature of the mode switch, the contrast between the Q-mode’s enhanced X-ray emission and reduced radio emission may well be illusory. Radio emission is only sampled on field-lines instantaneously directed towards us, and our sightline (34) makes only a grazing traverse of the polar cap. The core region of this polar cap, the probable site of X-ray hot spots, remains invisible to us at radio frequencies and may well change differently.

The totality of the mode transition in PSR B0943+10 – changes in radio sub-pulse behavior and profile, the appearance of a precursor and, now, the switching on and off in X-rays of a likely hotspot – implies that we are dealing with a rapid and global magnetospheric state change. Through radio and X-ray ‘before’ and ‘after’ snapshots, we have shown that a magnetosphere ten times the size of Earth completely changes personality within a few seconds, a near-instantaneous transformation that challenges our current understanding of pulsars and magnetospheres in general.
References and Notes:

16. Materials and methods are available as supplementary material on Science Online
40. XMMSAS-20110223-1801-1100: [http://xmm.esac.esa.int/sas/](http://xmm.esac.esa.int/sas/).

**Supplementary Materials**

www.sciencemag.org
Materials and Methods
Figs. S1, S2
Tables S1, S2, S3, S4, S5
References (35–40) [Note: The numbers refer to any additional references cited only within the Supplementary Materials]

**Acknowledgments:**

We thank the staff of XMM-Newton, the GMRT and LOFAR for making these observations possible. XMM-Newton is an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy. ASTRON and SRON are supported financially by NWO, the Netherlands Organization for Scientific Research. Two of us (JMR, GAEW) thank the NWO and ASTRON for their Visitor Grants. The used X-ray data can be retrieved from the XMM-Newton Science Archive at xmm.esac.esa.int/xsa. The applied B- and Q-mode window selections, derived from the GMRT and LOFAR observations, are listed in Table S2 of the SOM.
Fig. 1. Panel A: identification of the B- and Q-modes with LOFAR at 140 MHz, during XMM-Newton observation #1, showing the pulse intensity versus rotational phase and time. A 10-minute section (at the 4h mark) contaminated by interference is blanked out. Panel B: the measured signal-to-noise ratio compared with the nominal relative LOFAR sensitivity, changing with elevation throughout the observation (gray scale), normalized over the 4.0-4.5h range. Panel C: GMRT detection at 320 MHz of a Q- to B-mode transition in XMM-Newton observation #5. Color scale optimized to show the simultaneous disappearance of the precursor pulse at phase ~0.35. A 15-minute section (at the 1.5h mark) used for rephasing on a continuum source is blanked out.
Fig. 2. Aligned X-ray and radio pulse profiles of PSR B0943+10 in its B- and Q-modes. Panel A: there is no evidence for a pulsed signal in the B-mode X-ray data, the flat distribution showing constant emission from the pulsar. Panel B: the X-ray profile in the Q-mode represents a 6.6-σ detection on top of a flat constant level. The solid and dotted lines in the X-ray profiles are the Kernel-density estimator and ± 1-σ levels. The weak precursor, present only in the Q-mode, is clearly visible in the GMRT radio profile at 320 MHz at 52° (0.14 phase) prior to the main pulse, and verified to be also weakly present in the LOFAR Q-mode profile.
Fig. 3. Unabsorbed, i.e. corrected for absorption by interstellar gas along the line-of-sight, X-ray photon spectra of PSR B0943+10. Panel A: Total (i.e. pulsed and unpulsed) spectrum from spatial analyses of skymaps of Q-mode events from the XMM EPIC PN CCDs (filled symbols) and MOS1+2 CCDs (open symbols). The broken line shows the power-law component, and the dotted line the black-body component of the best fit. Panel B: The spectrum of the pulsed emission detected only in the Q-mode, analyzing the pulse profiles measured with the PN and MOS1+2 CCDs. The solid curve shows the best black-body fit. Panel C: The total spectrum, as in panel A, but here for the B-mode time windows. The solid line shows the best-fit power-law spectrum. The thermal black-body components in panels A and B are statistically the same; the non-thermal power-law components in panels A and C are also fully consistent with being identical. All error bars are 1σ. For fit parameters see Table 1.
Fig. 4. Panel A. The geometry of PSR B0943+10. The dipole magnetic axis is inclined at $15^\circ$ to the (vertical) rotation axis and the diagonal lines indicate the location of the null-charge surface, separating regions of positive and negative charge. As the pulsar rotates the observer’s line of sight maintains an angle of $9^\circ$ to the rotation axis, with $Q_{\text{max}}$ indicating the alignment when the radio pulse is seen (in both modes). The blue region indicates the supposed closed region, bounded by the light cylinder (at which the co-rotating magnetosphere reaches a rotation velocity equal to the speed of light) at 52,000 km. If, in a toy model, extinction of thermal X-rays from the polar cap is proportional to the extent of the traversed closed region ($\approx 10,000$ km at $Q_{\text{min}}$ and $\approx 500$ km at $Q_{\text{max}}$) then we obtain a sinusoidal fit to the observed $Q$-mode X-ray pulse (Panel B) so that maximum recorded emission corresponds to minimum extinction and vice versa. The lower horizontal line corresponds to the level of steady non-thermal emission and demonstrates that extinction of the thermal emission is near total at $Q_{\text{min}}$. The upper horizontal line then represents the level of actual unscattered X-ray emission from the polar cap.
Table 1. Spectral parameters for the best model fits to the X-ray spectra shown in Fig. 3. Fits are made with a black-body (BB) shape and/or a power-law (PL) shape for the total and the pulsed emissions in the Q-mode window and the total emission in the B-mode. The column density $N_H$ has been fixed at $4.3 \times 10^{20} \text{ cm}^{-2}$.

<table>
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<tr>
<th>Mode total / pulsed</th>
<th>Model</th>
<th>BB (kT) keV</th>
<th>PL index $\Gamma$ ($\alpha E^{-\Gamma}$)</th>
<th>BB flux, unabs $10^{-15}$ erg cm$^{-2}$ s$^{-1}$</th>
<th>PL flux, unabs $10^{-15}$ erg cm$^{-2}$ s$^{-1}$</th>
<th>$\chi^2_{\text{red}}$ / dof</th>
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<tr>
<td>B total</td>
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