The discovery of a transitive phenomenon in the radio emission of the mode-switcher PSR B0943+10

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Abstract
PSR B0943+10 is known to switch between two distinct, hour-long modes of radio emission, bright (B) and quiet (Q). The switches in both directions have so far been thought to occur instantly (on the scale of the spin period). We have found a transitive process around the Q-to-B-mode switch, which consists of two additional short-lived modes, each with distinct average profiles and subpulse drift rates. Based on observations at low radio frequencies, we examine the properties of these transitive modes and discuss their implications in the framework of the traditional carousel model of drifting subpulses.

Key words. stars: neutron

1. Introduction
PSR B0943+10 is a classical example of the so-called mode-switching pulsars, which are a small subset of radio pulsars that switch between several stable states of the electromagnetic emission. For PSR B0943+10, two modes have been identified so far: bright (or burst) and quiet (hereafter B mode and Q mode; see Suleymanova & Izvekova 1984). In the radio band, the average pulse shape and the properties of single-pulse emission both change between the modes, with the B mode being notorious for the organized temporal drift of individual subpulses (e.g., Deshpande & Rankin 2001).

In the X-ray band, the radio-mode switch is accompanied by changes in average pulse morphology and flux density (Hermsen et al. 2013; Mereghetti et al. 2016). The X-ray emission in both modes has a pulsed thermal component originating in the hot polar cap region on the neutron star surface, a few hundred kilometers away from the presumable origin of the magnetospheric radio emission (Bilous et al. 2014). Thus, some global-scale magnetospheric transformation is expected during mode transitions (Timokhin 2010; Cordes 2013).

Studying the properties of mode transitions may help to constrain the nature of this transformation, and searches for a peculiar single-pulse behavior around mode switches have been conducted regularly. To the extent of our knowledge, no such effects have been found so far: the recorded mode transitions occur instantly and abruptly (Bartel et al. 1982; Esamdin et al. 2005; Wang et al. 2007; Rajwade et al. 2021).

For PSR B0943+10, the mode transitions have been considered to be instantaneous as well, although there is no clear corroboration of this in the literature. In this paper we report the discovery of transitive phenomena around Q-to-B mode switches in several archival low-frequency observations conducted at 112 MHz with the Large Phased Array (LPA) at Pushchino Radio Observatory (PRAO), and at 25–80 MHz with the LOw-Frequency ARray (LOFAR; van Haarlem et al. 2013). This transitive state (hereafter T mode) lasts for about one minute or 60 pulsar rotations, thus being much shorter than the hour-long main modes. We describe the peculiar single-pulse properties during T mode and speculate on their implications for the mode-switching theories.

2. Observations and data processing

2.1. PRAO
The LPA is a transit instrument, and the duration of an observing session cannot exceed 3.5 min, where δ is the declination of the source. For PSR B0943+10, with its spin period \( P_1 = 1.0977 \text{s} \), this translates into a maximum of 194 pulses that are available per session. The pulses were recorded using a digital receiver with a bandwidth of 2.5 MHz, divided into 512 4.88-kHz spectral channels by a fast Fourier transform (FFT) processor. The actual total bandwidth taken into processing was 2.245 MHz. The signal was dedispersed to the frequency of 111.88 MHz (hereafter 112 MHz).

The narrow bandwidth of the channels reduced the effect of pulse broadening caused by interstellar dispersion delay. At 112 MHz, the total pulse delay within a single channel for the dispersion measure of PSR B0943+10 of 15.4 pc cm\(^{-3}\) is 0.5 ms, which is much shorter than the time resolution of 2.8672 ms. A more detailed description of the LPA digital receiver and data preprocessing is given in Suleymanova et al. (2012).

With a rotation measure of 15 ± 1 rad m\(^{-2}\) (Suleymanova et al. 1998), the Faraday modulation period at 112 MHz is about 1.6 MHz, which is comparable to the total bandwidth of the receiver. Thus, even though the LPA is a linearly polarized array, the recordings provide a reasonable estimate of the total intensity emission of the pulsar (see also Suleymanova & Rankin 2009).

2.2. LOFAR
PSR B0943+10 was observed with the low-band antennas (LBAs) of the LOFAR core stations at a center frequency of 53.8 MHz and in 25600 channels across a 78.1 MHz bandwidth.
The time resolution of the raw data was 0.65 ms. Observations were preprocessed with the standard LOFAR pulsar pipeline (Stappers et al. 2011). The signal was dedispersed and folded synchronously with the topocentric pulsar period that was obtained with the ephemerides from Shabanova et al. (2013). The dedispersion was subsequently refined using a more precise value of the dispersion measure, obtained by measuring the $v^2$ lag of the fiducial point in the B-mode profile of the same observations (Bilous et al. 2014). Each period contained 512 longitude bins, corresponding to a time resolution of about 2 ms. For further details of the data acquisition and preprocessing, we refer to Bilous et al. (2014) and Bilous (2018).

For both LOFAR and PRAO data, the subsequent analysis was performed on frequency-integrated pulse stacks, 2D arrays of the uncalibrated total intensity as a function of rotational longitude $\phi$ and time $t$, $S(\phi, t)$. In this notation, time is assumed to be constant within each rotational period of the pulse stack: $t = \text{[pulse number]} \times P_1$.

3. Overview of the radio emission in the main $B$ and $Q$ modes

3.1. Single pulses

Soon after the discovery of PSR B0943+10 in 1968 at PRAO (Vitkevich et al. 1969), a remarkable organized change in its subpulse positions had been reported by Taylor & Huguenin (1971). Further investigations at 430 MHz demonstrated that subpulses shift within the onpulse window with a rate of approximately $4\times4$ per stellar rotation (Backer et al. 1975).

Following Edwards & Stappers (2003) and Bilous (2018), the subpulse position $\text{pos}_{\text{drift}}$ can be mathematically expressed as follows:

$$\text{pos}_{\text{drift}}(\phi, t) \sim \exp\left\{ \frac{2\pi i t}{P_3} \right\} . \quad (1)$$

Here $\hat{P}_3$ is the observed modulation period along the lines of constant $\phi$, and $P_2$ is the longitudinal spacing between subpulses that are recorded within the same pulse period (see Fig. 1).

Both $\hat{P}_3$ and $P_2$ can be positive or negative, and the apparent direction of drift (i.e., whether pulses seem to march toward the leading or trailing edges of the profile) depends on whether $P_3$ and $P_2$ have the same sign. Following Edwards & Stappers (2003), we assumed that $P_3$ is always positive and let the sense of drift be determined by the sign of $P_3$.

$P_3$ is usually determined from the longitude-resolved fluctuation spectra (LRFS). LRFS consist of 1D Fourier transforms of the pulse stacks, computed over the lines of constant rotational longitude $\phi$. When drift is present, LRFS have two peaks at Fourier frequencies of $v_t = \pm 1/P_3$. In this case, $P_3$ can be assessed from the evolution of the complex phase of the Fourier transform with longitude. If $S(\phi, v_t)$ is the longitude-resolved Fourier transform of $S(\phi, t)$ computed over the lines of constant $\phi$, then from Eq. (1) it follows that

$$\text{Arg} \left\{ S(\phi, v_t = 1/P_3) \right\} \sim P_2\phi,$$

$$\text{Arg} \left\{ S(\phi, v_t = -1/P_3) \right\} \sim -P_2\phi. \quad (2)$$

Selecting the peak with the observed positive phase gradient will fix the sign of $\hat{P}_3$.

For PSR B0943+10, $\hat{P}_3 \approx -2.2P_2$ and $P_2 = 11^\circ$, meaning that subpulses drift to the trailing edge of the onpulse window (Bilous 2018). However, an absolute value of $P_3$ is commonly used in the literature (e.g., Deshpande & Rankin 2001, and other papers in this series). Since $P_3$ is close to a small multiple of $P_1$, the apparent drift is not obvious: the subpulses exhibit even-odd modulation together with a slow shift toward the leading edge of the average profile (see Fig. 2).

Measuring $P_3$ with LRFS does not solve the problem of aliasing. This problem is caused by the undersampling of the subpulse motion (subpulses can be observed only for a small fraction of the pulse period) and by volatile subpulse shapes, which prevents tracing the path of each specific subpulse throughout a pulse sequence (van Leeuwen et al. 2003). The true drift period $P_3$ in presence of aliasing is related to the observed $\hat{P}_3$ as

$$P_3 = n + \frac{P_1}{P_3}, \quad (3)$$

with the signed integer $n$ being the degree of aliasing. The true direction of the drift rate can be different from the observed one.

Deshpande & Rankin (2001) determined $n$ to be 1 based on the fleeting $37P_1$ modulation of the subpulse intensity. This modulation was interpreted within the popular carousel model (Ruderman & Sutherland 1975). In this model, the pulsar emission comes from discrete spots located on a ring centered on the magnetic pole. The slow rotation of the carousel causes the observed subpulse drift. Deshpande & Rankin (2001) argued that in their observations, the individual subpulses retained their relative amplitude distributions for approximately $256P_1$, which allowed tracing individual subpulses and resolving aliasing. An amplitude modulation like this is extremely rare; only two other instances have been found despite extensive searches (Backus et al. 2011; Bilous 2018).

PSR B0943+10 is unique in its slow consistent evolution of the drift properties. Rankin & Suleymanova (2006) have found that the PSR B0943+10 subpulse drift rate changes exponentially by some 5% during several hours after $B$-mode onset with a characteristic time of about 73 min. The change is faster at $B$-mode onset. Later it was found that this behavior is independent of observing frequencies between 40 and 327 MHz and over a timescale of several years (Rankin & Suleymanova 2006; Backus et al. 2011; Suleymanova & Pugachev 2017; Bilous 2018; Suleymanova et al. 2021).
4. Transitive phenomenon around the Q-to-B transition

4.1. Identification of the Tb and Tq modes

Figure 2 shows examples of individual pulse sequences for some of our observations. In general, the difference between the B and Q modes is evident to the naked eye. In B mode, individual pulses form two columns corresponding to components of the average profile. The drift of subpulses near the central

In turn, emission in the Q mode is stable in the sense that no gradual changes in its properties have been recorded. Despite systematic searches, no drifting subpulses were detected in the Q-mode (Suleymanova & Izvekova 1984; Backus et al. 2010), except for an occasional feature at 0.0275 cycles/P₁ corresponding to P₃ = 36.4P₁ (Rankin & Suleymanova 2006). The origin of this feature is unclear, and no similar features have been found since then (Bilous 2018).

3.2. Average profile

In both modes, the average pulse profile is composed of two components of equal width that move away from each other at lower frequencies. The full width at half maximum of the components is about 7.2 for the B mode and 11.5 in Q mode and does not show a strong dependence on frequency between 40 and 80 MHz (Bilous et al. 2014). Recently, Suleymanova et al. (2021) have shown that the width of the average pulse components in the B mode is constant over the wider frequency range of 62–1391 MHz, with the separation between components increasing rapidly toward lower frequencies in accordance with a power law,

\[ s(\nu) = 130.8 \times \nu^{-0.56} \]
longitudes is not visible due to a decrease in the average pulse intensity in the saddle between the components. In Q mode, subpulses are distributed randomly within the on-pulse window. Panels 150518, L99010, L102418, and 260520 show the unusual behavior of subpulses around Q-to-B mode transitions. When the subpulse drift recommences after the end of the Q mode, subpulses drift through entire on-pulse window for a short period of time, and unlike later on, there is no fading of subpulses at the central longitudes. During this period, the on-pulse window is somewhat narrower than in the well-established B-mode sequences.

These features allowed us to identify these particular sequences of pulses as a new mode, which we designated transitive B-like mode, or Tq modes. The Tq mode has been recorded in all available observations except for session L169237 in Bilous et al. (2014). Compared with the sessions presented on Fig. 2, the signal-to-noise ratio (S/N) of the pulsed signal is lower there, and emission is modulated by scintillation, with one of the intensity troughs coinciding with Q-to-B transition (see Fig. 1 in Bilous et al. 2014).

In panel 260520, the subpulse drift pattern characteristic for the Tq mode is observed in the 30-s interval between B-mode pulses. There are no Q-mode pulses in this record, but the shape of the average B-mode pulse profile, with two equally bright components, indicates that the Q-to-B switch occurred a few minutes before the start of the observing session (Rankin & Suleymanova 2006; Suleymanova & Rankin 2009). The presence of Tq-mode pulses within the B-mode sequence suggests that the B-mode emission in the first minutes after mode onset is unstable.

The Tq mode is not the only transitive phenomenon around Q-to-B switches. Some time before Q-mode cessation, groups of pulses appear that slowly drift toward the trailing edge of the on-pulse window. This drift is present in all but one Q-to-B transitions observed. We labeled these slowly drifting pulses transitive Q-like modes, or Tq modes.

Both Tq and Tq modes exhibit drifting subpulses, and the presence of this drift was used to establish mode boundaries. However, the Tq mode does not immediately follow the Tq mode. Between them there is a gap of several spin periods with very rare single pulses resembling those of the Q mode. Interestingly enough, the only observed B-Tb-B transition also exhibits the absence of emission for a few seconds before the Tb mode starts (Fig. 2, panel 260520).

Because the transit time of PSR B0943+10 through the BSA beam is much shorter than the typical duration of its main modes, records of mode switching are rare, with only five sessions with Q-to-B transitions being found in the archives. The subpulse intensities for these five records are shown in Fig. 3, with different modes shown by different colors. There are no Q-mode pulses in the 090112 session. The low values of the subpulse drift rate indicate that the first 42 pulses correspond to the Tb mode and the remaining pulses to the B mode. In addition, the shape of the averaged pulse in B mode with the ratio of the components R(2/1) = 2.1 clearly indicated that the Q-to-B switch occurred shortly before the start of the observation session (Rankin & Suleymanova 2006; Suleymanova & Rankin 2009).

In five cases in Fig. 3, the Tq mode is much shorter than the Tb mode, and in one session (230920), it is completely absent. The duration of the Tq mode varies between sessions, comprising 17–66 spin periods, or 19–69 s. At lower frequencies, the two transitions that were recorded exhibit shorter Tq modes of only 13 s, but this may be just a coincidence. More low-frequency observations are needed to explore the Tb mode duration below 100 MHz.

To our surprise, the opposite, B-to-Q mode transitions were featureless (e.g., panel 221219 in Fig. 2). No transitive phenomena were found in any of our recordings.

4.2. Subpulse drift

4.2.1. Tb and Tq modes

The Tb and Tq modes are much shorter than pulse sequences that are typically used to compute LRF spectra and determine the drift parameters in the B-mode. Cutting the usual several-hundred pulse sequences around Tb and Tq modes pollutes the spectra with either B-mode drift or Q-mode noise, which decreases the S/N of the transitive mode spectra peaks. This is detrimental for the fainter Tq-mode sequences. However, finding peaks on LRF spectra usually involves integrating spectral power within the onpulse window, which does not take the regularity of the longitude separation between subpulses in the same period into account (this information is stored in the complex phase of LRF spectra). The 2D FFT transform (Edwards & Stappers 2003) does not have this disadvantage and thus is better suited for

Fig. 3. Five records of Q-to-B mode switches from the archives of 112 MHz observations. The intensity of subpulses in units of S/N is given as a function of pulse number. Individual modes are highlighted with different colors (black for B mode, green for Q mode, red for Tb mode, and magenta for Tq mode).
measuring the drift parameters of the short pulse sequences of the Tq and Tb modes.

To measure $\hat{P}_1$ and $\hat{P}_2$ simultaneously, we performed 2D FFT transforms in a fixed-size window sliding along the pulse number axis. The window size was ten pulses by 22$°$ or 40$°$ of the rotational longitude for LPA and LOFAR observations, respectively. The sliding step was 2$\hat{P}_1$. In order to measure the position of the FFT peak more precisely, sequences of zeros were added to each data row, boosting the nominal Fourier frequency resolution by a factor of 10. Formal errors on $\hat{P}_1$ and $\hat{P}_2$ were derived from the frequency resolution of the padded data transforms, but the real, noise-influenced errors are supposed to be larger by a factor of a few.

To estimate the significance of recorded features, we performed the same feature extraction procedure on the original pulse sequences, but with randomized subpulse positions. The randomization was done by shuffling the pulse periods within the groups of four phase bins. In this way, the average shape of ten-pulse integrations was preserved, while any periodicity along the axis of constant longitude was destroyed and the periodicity in the orthogonal direction was attenuated. This procedure was performed 1000 times, and the percentile of the peak in the FFT spectrum of the real data was compared to the distribution of the corresponding peaks of the simulation. Based on the total length of the pulse sequences we explored, the total number of chance detections above our threshold is estimated to be between 0.5 and 2 for short sequences of pulses of the transitive modes. In some cases, we were forced to calculate $f_3$ on longer pulse sequences that included nonmodulated $Q$-mode emission. For the LOFAR data, we used the mean values of the Tb modes from Fig. 5, with the error bar corresponding to the standard deviation of $f_3$.

Examples of the 2D FFT spectra are given in Fig. 4. Most of the features we detected came from Tb and B modes, where subpulse drift is visible to the naked eye. In all but one session, there had been significant detections of drift periodicity in the $Q$ mode shortly before the $Q$-to-$B$ transition (Tq mode). In both transitive modes as well as in the $B$ mode, the feature at positive $P_2$ had negative $\hat{P}_1$, meaning that pulses drifted to the trailing edge of the onpulse window.

$\hat{P}_3$ in the Tq mode varies substantially between mode instances, ranging from approximately 3.2$\hat{P}_1$ to 6.7$\hat{P}_1$. It also exhibits variation within the Tq mode itself. For the Tb mode, $\hat{P}_1$ stays closer to the $B$-mode values; most of the time, it is larger than in the $B$ mode. The jitter of measured $\hat{P}_3$ in the $B$ mode is partially due to noise influence, and partially intrinsic: Bilous (2018) reported that LRF spectra on 512-pulse sequences had multiple peaks with a frequency spread on the order of $0.01\hat{P}_1/\hat{P}_3$.

Interestingly enough, the subpulse separation remains more or less constant throughout the Tq, Tb, and $B$ modes, varying chaotically around 11° with a magnitude of $1° - 2°$. $P_3$ for the same LOFAR sessions was also measured in Bilous (2018) using a more precise phase-track method on 512-pulse sequences, which takes the observed increase in the subpulse separation at the edge of the onpulse window due to the curved LOS path into account. In their work, $P_2$ at the fiducial longitude (middle of onpulse window for PSR B0943+10) is 10°6 − 10°8, with $P_2 \approx 18°$ at +15° of the spin longitude. In our case, the 2D FFT gathers information from the entire onpulse window, thus our $P_2$ is larger. Since pulse sequences comprise only ten pulses, the illumination of the onpulse window is quite uneven, bringing additional variability in the measured $P_2$.
Fig. 5. Absolute value of the modulation frequency around the lines of constant spin phase ($f_3 \equiv |P_1/\dot{P}_3|$) as a function of time for the pulse sequences from Fig. 2. Horizontal error bars mark the edges of the ten-pulse samples used for $f_3$ calculation. Vertical error bars show the nominal frequency determination error taking into account the zero-padding. For each subsample, only $f_3$ with the highest S/N is plotted (see text for details on S/N estimates). Only peaks that were stronger than 99.5% of the simulated sample are shown. The vertical lines mark the mode edges. All points here correspond to negative $P_1$ except for the empty point for session L99010. For the PRAO sessions, the absence of $f_3$ points near the observation end is due to pulsar signal attenuation.

from the current work as well as LOFAR $B$-mode measurements from Bilous (2018), and Arecibo 327 MHz values from Rankin & Suleymanova (2006). As indicated in these studies and in Backus et al. (2011), the frequency of the amplitude fluctuations varies with time according to the exponential law (dashed line), where $t$ is the time since mode onset (min),

$$f_3 = 0.471 - 0.022 \times e^{-t/73}. \quad (4)$$

This equation limits $f_3$ to the range of 0.449–0.471 cycles/$P_1$. Numerous observations of PSR B0943+10 at 112 MHz showed that for roughly 2.5% of $B$-mode pulse sequences, $f_3 < 0.449$ cycles/$P_1$. Thus, Suleymanova & Pugachev (2017) have proposed a better power-law parameterization that encompasses all $B$-mode $f_3$ measurements,

$$f_3 = 0.439 \times 10^{0.0126}. \quad (5)$$

In the Tb modes, $f_3$ varies in the range of 0.428–0.439 cycles/$P_1$ with a mean value of 0.434±0.004 cycles/$P_1$ that is significantly lower than has ever been measured for the $B$ mode. Nevertheless, these values can be considered as compatible with the power-law $f_3$-time dependence in the $B$ mode. For both functions in Fig. 7, $t = 0$ at $B$-mode onset. During the Tb mode, $t < 0$, thus its $f_3$ values were not included in the power-law fitting procedure. The average value of $f_3$ at $B$-mode onset following the Tb mode is 0.449±0.002 cycles/$P_1$, as was expected.

4.3. Average pulse profile during transitive modes

Figure 8 shows the average profiles for all four modes in two LOFAR sessions with the Q-to-$B$ transition. The shape of the average profile in transitive modes varies between the sessions and is dominated by the individual strong pulses. Because of the small number of modes and their relative shortness, it is hard to compare the average profiles in transitive modes with the regular $B$ and $Q$ modes, but it can be stated that neither the Tq nor the Tb mode exhibits two distinct separate components like the $B$ mode.
Fig. 6. Examples of onpulse-integrated LRF spectra calculated for 91-pulse sequences containing the Tb mode (150518, red line), early B mode (260520, blue line), or late B mode (221219, black line). Corresponding frequencies are 0.428, 0.449, and 0.472 cycles/\(P_1\).

Fig. 7. Compilation of observed \(f_3\) values as a function of time since B-mode onset. Previously published \(f_3\) measurements are shown by black stars (Arecibo, 327 MHz) and black crosses (LOFAR, 30–80 MHz). The 112 MHz measurements for the Tb and B modes from this work are shown with red circles and crosses. The \(f_3\) value for 91 B-mode pulses right before a B-to-Q mode transition (session 221219) is plotted at an arbitrary time mark of 250 min. LOFAR Tb-mode \(f_3\) measurements are shown with blue triangles. The points around \(t = 180\) min show typical \(f_3\) error bars for PRAO and LOFAR measurements from this work. Horizontal lines mark the range of validity of the exponential fit by Backus et al. (2011, dashed magenta line). The black line shows the power-law fit from Suleymanova & Pugachev (2017). The measurements for the Tb mode agree well with a power-law fit.

PRAO observations offer larger mode samples and also longer instances of the Tb mode. Figure 9 shows the average profiles integrated within B and Tb modes for the three PRAO sessions that exhibited prominent B-mode component peaks to facilitate alignment between sessions. The bottom panel presents integrated profiles for these three sessions, comprising 135 individual pulses for the Tb mode and 390 pulses for the B mode. At 112 MHz, the Tb mode clearly has no separate components, and the profile is asymmetric and skewed to earlier spin longitudes.

Interestingly, the shape of the pulse profile in the averaged Tb mode closely matches the composite Q + B profile recorded close to the B-to-Q transition (session 221219, Figs. 10a,b). In session 221219, the B-to-Q switch occurred in the middle of the observation. For comparison, the average Tb-mode profile from Fig. 9 was shifted by 5.7 ms toward earlier spin longitudes. This close resemblance of the pulse shapes could indicate that around the Q-to-B switch, the regions responsible for the Q and B modes emit simultaneously and that their contribution is equal. This is possible only under the condition that the B and Q pulses are emitted from two independent regions in the pulsar magnetosphere. In the core/cone model (Rankin 1983), the Q and B modes in PSR B0943+10 are associated with the core and conal emission beams that emit alternately. The discovery of the transitive modes allows us to suggest that over some short time, these two independent regions may emit simultaneously.

If the Tb-mode emission is indeed a superposition of the Q and B modes, then the 5.7 ms delay is naturally explained by the evolution of the onpulse window location throughout the B mode. It is known that during the lifetime of each B-mode instance, the average pulse shifts toward later longitudes. The total shift varies from 4 to 6 ms per B-mode duration (Bilous et al. 2014; Suleymanova & Rodin 2014; Suleymanova & Pugachev 2017). Thus, the Tb-mode emission is a superposition of the late B mode and the Q mode. During the instantaneous Tb-to-B switch, the emission window resets at earlier longitudes, and the slow shift to the later longitudes continues during new the B-mode instance. Within this interpretation, it is hard to explain the B-Tb-B sequence of the 260520 session, however, where both B-mode sequences framing the Tb mode exhibited the properties of the early B mode.

Observational evidence speaks against the Q-mode emission being produced by a core component in the core/cone model of the pulsar radio beam. First of all, this evidence includes the appearance of organized subpulse drift (Tq mode) within the sequence of Q-mode pulses right before the Q-to-B switch and the crude similarities between the shapes of the average profile in both modes. Moreover, at frequencies lower than 100 MHz, Q-mode profiles exhibit conal components that separate progressively (Suleymanova et al. 1998; Bilous et al. 2014). It was shown that for PSR B0943+10, the sightline makes only a grazing transverse of the polar cap (Deshpande & Rankin 2001), and the scenario in which the observer misses most of the core radiation because of this peripheral sightline was previously put forward to explain the relative faintness of the radio emission of PSR B0943+10 during its bright X-ray mode (Hermsen et al. 2013; Rankin et al. 2020). Another scenario can be proposed in which the core radio beam is missed completely and all modes observed in PSR B0943+10 originate from conal beam shape

Corresponding frequencies are 0.428, 0.449, and 0.472 cycles/\(P_1\).
Fig. 9. Average pulse shape of the Tb mode (red line) and the B mode (black line with crosses) for sessions (from top to bottom) 150518, 260520, and 090112. Profiles for different days were aligned by the leading peak of B-mode profile. The lowest panel shows profiles averaged over these three sessions.

Fig. 10. Comparison of the mode-separated average profile shapes for observations at 112 MHz. (a) Mode-separated average profiles for session 221219, where the B-to-Q transition occurred in the middle of the observation. Violet and green lines correspond to the B and Q modes, respectively, and the thin blue line shows the composite B + Q profile. (b) B + Q profile (blue line) superposed on the average Tb-mode pulse profile (red line) shifted by 5.7 ms toward earlier spin longitudes. (c) B-mode pulse shape evolution starting from its onset (session 260520, dotted line) up to cessation (session 221219, violet line), together with Tb-mode pulse (red line) shifted by 5.7 ms toward earlier spin longitudes. (d) Tq-mode profile (blue line) accumulated from sessions 150518 and 051112. The B-mode profile in 260520 is given for comparison. Profiles for different days were aligned by the leading peak of the B-mode profile.

Observations at 112 MHz show that the width of the onpulse window stays similar throughout all four modes (Fig. 10). It is considered to be determined by the size of the polar cap with the radius $R_{\text{out}}$. Within the framework of the traditional core/cone model of pulsar radio emission (e.g., Rankin 1983, and other papers in this series), the width of the conal components in the average pulse profile is set by the thickness of the pair-producing ring in the polar gap: $W_{\text{ring}} = R_{\text{out}} - R_{\text{inn}}$, where $R_{\text{inn}}$ is the inner radius of the ring. We suggest that the transitions between modes are accompanied by variations in the inner radius. This can explain the gradual increase in the component width over the B-mode lifetime and the appearance of drifting subpulses at the central longitudes in the Tb and Tq modes. At B-mode onset, the two components of the average pulse profile are well separated, with an intensity in the saddle region close to zero below 100 MHz. The width of the components is at its minimum and grows with B-mode age (Bilous et al. 2014). For the leading component 112 MHz, the width can increase by as much as 40% (Suleymanova & Rodin 2014). This effect is well demonstrated in Fig. 10c, where the profiles of the average pulse for the onset and the end of the B mode are shown. The width of the first component at the level of half maximum increases from 15 to 24 ms, that is, by 60%. The same panel shows the profile of the average Tb mode with a width of 30 ms. The total change in profile width between the Tb and early B mode is 100%. With this significant increase in the width of $W_{\text{ring}}$, the central longitudes become illu-minated for our line of sight, and we observe drifting subpulses close to the fiducial longitude in transitive modes.

Figure 10d shows the Tq-mode profile obtained at 112 MHz after averaging 20 pulses using sessions 150518 and 051112. It is worth noting that because of the short duration of the mode, its average profile is distorted by bright pulses. However, comparison of the Tq mode to the Q mode profile (Fig. 10a) reveals similarity in profile shape as far as they are both skewed to the trailing side (unlike the B mode). A similar behavior is observed in the LOFAR data (Fig. 8).
5. Summary

We reported the discovery of a transitive process that takes place for about a minute around a Q-to-B-mode switch. This process consists of two stages, which we labelled Tb and Tq modes.

5.1. Tb mode and its comparison to the B mode.

1. This mode precedes the B-mode onset by 40±25 s. The duration of the Tb modes exhibit larger variations from one instance to the next, ranging between 12P1 and 66P1.

2. Similarly to B mode, the individual subpulses drift from the leading to trailing edge of the onpulse window, but the drift now extends through the whole onpulse window, including the central spin longitudes.

3. The amplitude modulation frequency in the Tb mode varies in the range of 0.428−0.439 cycles/P1 with a mean value of 0.434±0.005 cycles/P1, that is significantly lower than the f3 values measured for the B mode. Nevertheless, these values agree with the power-law f3 evolution throughout the B mode.

4. The average pulse profile in the Tb mode is skewed to the leading edge, similar to the B mode, but it does not have resolved conal components.

5. The Tb mode sometimes occurs within an early B-mode instance.

5.2. Tq mode and its comparison to the Q mode.

1. The Tq-mode occurs within the late Q mode, and unlike the latter, it has a specific subpulse drift pattern. This mode precedes the Tb-mode onset by 34±7 s and lasts for about 10−22P1. In one session, no Tq mode was recorded, but the S/N of the recording was quite low.

2. As in the Tb and B modes, subpulses in the Tq mode drift toward the trailing edge of the onpulse window. The drift frequency f3 varies from 0.149 to 0.312 cycles/P1 from one observation to the next, with an occasional strong variation of f3 within the mode.

3. The average pulse profile in the Tq mode has a tendency to be skewed to the trailing edge, which is characteristic of the Q mode.

6. Discussion

Short-lived mode sequences have previously been observed from several pulsars, for example, PSR B1859+17 (Rajwade et al. 2021), PSR J1326−6700 (Wen et al. 2020), and PSR J1909−3744 (Miles et al. 2022). The peculiarity of the transitive modes of PSR B0943+10 lies in the fact that they usually appear in a one-minute interval around the switch between the two main hour-long modes, the Q and B mode. These two modes show similarities to the main modes and are considered as submodes, which is reflected in their designation.

Gil & Sendyk (2000) argued that subpulse drift is observed when a quasi-central spark is formed at the local pole of a sunspot-like surface magnetic field. This fixed spark prevents other sparks from moving toward the pole, restricting their motion to slow drift around the pole. Although little is known about the configuration of the small-scale magnetic field of PSR B0943+10, we can qualitatively apply this model to the PSR B0943+10 mode sequences. During the Q mode, no central spark is formed, sparks quickly move toward the magnetic pole, and subpulses are observed at random onpulse longitudes. At the end of the Q mode, the anchor spark appears, causing Tq-mode sequences. The carousel rotates relatively slowly and exhibits much variation from one mode instance to the next, as well as within the Tq mode. This might reflect fast-paced changes in the spatial or temporal variations in the accelerating potential in the polar gap. Subpulses are seen in the central region of the onpulse window, indicating a larger width of the carousel. Subpulses briefly disappear (except for maybe a few pulses) during the null-like period between the Tq and Tb modes. During the Tb mode, the carousel width remains large, but it then gradually decreases throughout the B mode. The carousel rotation rate evolves in a similar manner, more rapidly during the Tb and early B mode, and more slowly at the end. During the reverse B-to-Q transition, the anchor spark disappears and the drift ceases.

Drifting subpulses are traditionally used as a voltmeter to measure the gradient of the accelerating potential across the polar cap (van Leeuwen & Timokhin 2012). When a small degree of aliasing in the B, Tb, and Tq modes is assumed, the large and fast fractional change of P1 in the Tb and Tq modes (compared to the more gradual smaller change over the course of the B mode) means some rapid and powerful magnetospheric current rearrangements.

The timescales of mode switching for PSR B0943+10 and other mode-switching pulsars are much longer than the characteristic timescales of force-free magnetospheres (~P1). It has been conjectured that mode switching is a manifestation of metastable magnetospheric states, produced by nonlinear interaction between the neutron star magnetic fields, polar cap cascades, and current sheets (Timokhin 2010). In particular, these quasi-stable states can have different open field-line zone sizes and/or different current density distributions within the open field-line zone. If switches between the B and Q mode are accompanied by a shrinking or expanding of the open field-line zone (the polar cap for the external magnetic field of the dipole), then, assuming that the radio emission comes from the last open field lines, we may infer the polar cap radius from the width of profiles in the B and Q modes. Taking 0.06 of spin phase for the former and 0.05 for the latter, for the plausible ranges of the inclination angle and LOS impact angle (Bilous 2018), we may infer a 5% shrinking of the polar cap radius in the Q mode. According to Timokhin (2010), this change would correspond to a 20% change in spin-down rate between the B and Q modes. This change cannot be directly detected for the 3 × 10−13 s−1 spin-down rate of PSR B0943+10 considering that mode switching occurs on a timescale of hours. However, if the relative fraction of Q and B modes changes slowly over time, this would affect the overall spin-down rate. A similar effect was detected for PSR B1828−11, where the variable rate of mode transitions was directly related to the spin-down changes (Stairs et al. 2019).

Our crude estimate above implies that the size of polar cap is larger in the B mode. Rigoselli et al. (2019) performed direct fitting of the mode-separated thermal X-ray spectra and light curves. Generally, the Q mode has larger polar cap size and higher temperature than the B mode, but the error contours do permit a 5% larger polar cap radius in B mode. For this, Q-mode polar cap should have a temperature that is about a 20% higher.

On the other hand, Szary et al. (2015) proposed that mode switching reflects the switching between two types of partially screened gaps, with different pair production and a gap-screening mechanism. For both types, the polar cap temperature should be roughly the same in order to maintain the thermostat mechanism of the partially screened gap. This does not contradict the results of Rigoselli et al. (2019) either, although in this case, the size of polar cap in the Q mode should be larger. We
must note that the heating patterns are generally poorly known, and the polar cap is almost certainly not illuminated uniformly. Radio emission may also be a poor indicator of the polar cap size. It comes from the same field lines in both modes, but shifts in height.

The two transitive modes so far exhibited quite large variations in their properties from one session to the next. In order to deepen our understanding of the carousel formation, more mode instances should be explored, preferably in a wide frequency range.

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