J. Astrophys. Astr. (1998) **19**, 1–18

Individual and Integrated Pulse Properties of PSR B0943+10 Involved in the Mode-Changing Phenomenon

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Received 1997 June 24; accepted 1997 December 17

Abstract. The characteristics of the "burst" (B) mode and "quiescent" (Q) mode pulse sequences—long known from studies at or below 103 MHz—are identified at 430 MHz for the first time. An 18-minute, polarimetric observation begins with a long B-mode sequence, which has a higher average intensity, regular drifting subpulses, and a preponderance of primary polarisation-mode radiation. An abrupt transition to a Q-mode sequence is then marked by **a**) weaker average intensity, but occasional very bright individual subpulses, **b**) a complete cessation of drifting subpulses, with disorganized subpulses now being emitted over a much wider longitude interval, and **c**) near parity between the primary and secondary polarisation modes, resulting in pronounced depolarisation, both of individual pulses and the average profile.

Careful study, however, of profile changes before and after this mode change reveals slower variations which both anticipate the abrupt transition and respond to it. A slow attenuation of the intensity level of the dominant component is observed throughout the duration of the B-mode sequence, which then accelerates with the onset of the Q-mode sequence. This slow variation appears to represent a "pre-switching transition" process; and the combination of effects on slow and abrupt time scales are finally responsible for the formation of the characteristic B- and Q-mode average profiles.

Key words. Pulsars—B0943+10—mode changing—polarisation.

1. Introduction

Much of what is known about PSR B0943+10—including its discovery—has resulted from meter-wavelength observations at the Pushchino Observatory.[1] The remarkable burst-like emission attracted early attention (Vitkevich *et al.* 1969), and subsequent observations at 103 and 62 MHz first identified the two distinct average-profile forms associated with its more intensive burst-like (B) mode and "quiescent" (Q) mode (Suleymanova & Izvekova 1984).[2] Linear polarisation studies, on both an average and individual-pulse basis, have also been carried out at the Pushchino Observatory at 103 MHz and below, by analyzing the spectral variations of 0943+10's Faraday-rotated signal (Suleymanova *et al.* 1988; Suleymanova 1989).

Pulsar 0943+10 shows most of the properties which Bartel *et al.* (1982) have identified as characteristic of the "mode switching" phenomenon as follows:

- The components of its integrated pulse profile change their relative intensity, and the transformation of its double-resolved B-mode profile into an unresolved double in the Q-mode entails alterations in the longitudinal spacing of its components.
- The changes in 0943+10's integrated profile are accompanied by changes in the character of its subpulse-drift behaviour. The highly regular drift pattern with a P_3 value of about 2.1 cycles/period (Taylor & Huguenin 1971; Backer *et al.* 1975; Sieber & Oster 1975; Suleymanova & Izvekova 1984) is characteristic of the B-mode. On the other hand, observations at 103 MHz have shown no such feature in the Q-mode fluctuation spectrum (Suleymanova & Izvekova 1984).
- The fractional linear polarisation of the weaker Q-mode integrated profile is generally less than that of the B-mode.
- The mode switching occurs simultaneously at different frequencies—that is, at 40 and 103 MHz (this paper).
- In addition to these other characteristics, it is worth noting that the pulsar is nearly unique in exhibiting comparable lifetimes in its respective B and Q modes.

Helfand *et al.* (1975) have pointed out that "mode switching" pulsars are similar in being relatively old—that is, with periods $P > 0.7$ s and characteristic ages $\tau = P/2\dot{P} > 2.8 \times 10^6$ yrs. With a period of 1.097 s and a τ of 4.9×10^6 yrs, pulsar 0943+10 is thus typical of this class.

All of these features, except the drifting behaviour, pertain to the integrated profile. We know rather little about how the mode-switching phenomenon is manifested on rotational-period time scales, so studies of long individual-pulse sequences are important for extending the range of our understanding. Unfortunately, observations at the Pushchino Observatory are limited to a few minutes duration by the transit

[1] The pulsar's unusually steep spectrum makes it both one of the strongest pulsars at low frequency and difficult to observe at higher frequencies. To our knowledge the pulsar has never been detected above about 600 MHz (Comella 1971), and we know of no published profiles at frequencies higher than 430 MHz. That one published by Rankin & Benson (1981) is typical of those at decimeter wavelengths; it has the simplest form and was classified as conal single (S_d) by Rankin (1986, 1993a, b). The extreme tangential traverse of our sightline through this pulsar's conal beam supports this classification and furthermore argues that it would ultimately miss the pulsar's beam at high enough frequency—a circumstance which goes far toward explaining its very steep spectrum.

[2] The designations of the two modes follow those given by Fowler *et al.* (1981) in discussing pulsar B1822−09.

nature of its BSA and DKR-1000 instruments. Consequently, Pushchino observers are almost never able to "catch" the pulsar in the process of switching between its two modes, since the modal lifetime is estimated to be typically half an hour (Suleymanova & Izvekova 1984).[3]

Individual-pulse polarimetry at 430 MHz of modest quality was carried out at Arecibo Observatory in 1974, and much improved observations at this frequency were conducted in October 1992. Fortunately, although pulsar 0943+10 is generally rather weak at this frequency, it exhibits periods of enhanced intensity, due to some combination of scintillation and intrinsic causes. Both observations were recorded during such "bursts", and the latter 18-minute, fully polarimetric observation—recorded when the pulsar was particularly bright—has been analyzed to compare with 103-MHz Pushchino observations.

Comparison of the 430- and 103-MHz observations has made it possible to—

(a) Identify 0943+10's two distinct emission modes in the 430-MHz sequence of pulses for the first time. Groups of pulses at the higher frequency were found which appear analogous to those which constitute the characteristic B- and Q-mode profiles observed at and below 103 MHz, where a large body of observational data is at our disposal.
(b) Make both average and individual-pulse polarisation measurements of pulse sequences belonging to the two distinct modes. Individual-pulse polarimetry at 430 MHz, together with that at 103 MHz, has shown marked changes in the frequency of occurrence of the linear polarisation angle (PA). These polarisation variations, together with alterations in the overall intensity, determine the structure and polarisation of the average profile.
(c) Study both rapid and slow variations in the intensity of individual pulses involved in the mode-switching process. One of the most salient characteristics of the mode-changing phenomenon is its rapid switching time—on the order of a pulsar period or less. Only in the case of one observation of one pulsar, PSR B0355+54, has evidence for a slower modal transition been suggested—there, a 12-minute onset of the abnormal mode at 11-cm wavelength (Morris *et al.* 1980).

The Arecibo observations of PSR 0943+10 provided a sequence of nearly 1000 pulses containing clear B- and Q-mode sequences as well as a transition interval of special interest. We shall show that 0943+10 exhibits changes on both long and short time scales during its mode-changing process. A slow attenuation of the dominant B-mode component over 18 minutes (which can be regarded as a "pre-switching transition process") occurs before and for some time after the sudden enhancement of trailing-edge radiation which is characteristic of the Q mode. The combination of these two effects, on completely different time scales, finally produces the observed integrated-profile changes.

This "pre-switching transition process" in pulsar 0943+10 is remarkable and constitutes one of the main results of our study, which we will discuss in detail below. The identification of gradual changes associated with a modal transition in PSR 0943+10, together with the similar phenomenon in 0355+54, sheds more light on the character of the mode-changing phenomenon overall.

[3] Phillips & Wolszczan (1989) also estimated the time scale for mode changing as at least 30 minutes from observations at 25 MHz.

2. Observations

The low frequency observations were conducted in 1990 using the 103-MHz BSA and 40/61-MHz DKR-1000 telescopes at Pushchino Radio Astronomy Observatory, the 61-MHz observations in January and simultaneous 40- and 103-MHz observations in December. The signals from these linearly polarised arrays were fed to radiometers with 64×20-kHz contiguous channels (at 61 and 103 MHz) and/or to 32×5-kHz contiguous channels (at 40 MHz) in order to measure the total intensity and its spectral variations across the passband. The dedispersed signals were referred to the frequency of the first channel—that is, to 103.130, 61.194 and 39.898 MHz (hereafter 103, 61 and 40 MHz).

By observing a linearly polarised pulsar signal at adjacent frequencies, the rotation measure (*RM*) can be obtained, which for observing frequencies of 40, 61 and 103 MHz, gives a value of 15 ± 1 rad/m^2. The Faraday-modulation period Δf is related to the frequency f by $\Delta f = 1.748 \times 10^{-5} f^3/RM$ (Smith 1968). In that the total passband exceeded the Faraday-modulation period at each of the three frequencies, the total intensity of the dedispersed pulses provides a reasonable estimate of Stokes parameter I. The fractional linear polarisation and its associated position angle were then determined for each sample—using a technique developed at Pushchino (Suleymanova *et al.* 1988)—from the Faraday-rotation-induced, quasi-sinusoidal intensity modulation across the passband. The time resolutions were 6.9, 5.2 and 6.9 ms at 40, 61 and 103 MHz respectively. Each set of 0943+10 observations comprised some 280 individual pulses at 103 MHz and some 400 at 40 and 61 MHz. The individual-pulse analyses were carried out using the strongest 103-MHz, B-mode and Q-mode sequences available, those observed on 27th and 28th December 1990 respectively. Of these, pulses with sample intensities exceeding a threshold of five standard deviations in the off-pulse noise level were selected for the polarisation analysis presented below.

The 430-MHz observations were made at the Arecibo Observatory in a single observing session on the 19th October 1992. These individual-pulse observations used the Arecibo 40-MHz correlator in a gated mode, which "dumpted" the ACFs and CCFs of the right- and left-hand channel voltages at 1000 μs intervals during a window centred on the pulse.[4] Use of the 10-MHz bandwidth and the retention of 32 lags reduced dispersion delay across the bandpass to negligible levels. The resolution was then essentially the correlator dump time or 0.33°. In all cases the measured correlation functions were scaled, 3-level-sampling corrected, and Fourier transformed to produce raw Stokes parameters, which were in turn corrected for dispersion, Faraday rotation, instrumental delays, and all of the known feed imperfections. This procedure will be described in a forthcoming paper (Rankin *et al.* 1998). The observational parameters are summarized in Table 1.

3. Identification of the B and Q modes at 430 MHz

The polarisation properties of a sequence of 103-MHz individual pulses corresponding to the B- and Q-profile modes are given in the left-hand panels of Figs. 1 and 2,

[4] The Arecibo 40-MHz correlator is described by Hagen (1987) and the observing software by Perillat (1988).

Table 1. Data acquisition information.

	102.5 MHz		430 MHz	
	B mode	Q mode	B mode	Q mode
Dates	27th Dec. 90	28th Dec. 90	19th Oct. 92	19th Oct. 1992
Total bandwidth, MHz	1.28	1.28	10	10
Post-detection smoothing, ms	3	3	none	none
Time resolution, ms	6.9	6.9	1.0	1.0
Number of pulses in histograms	264	224	817	169

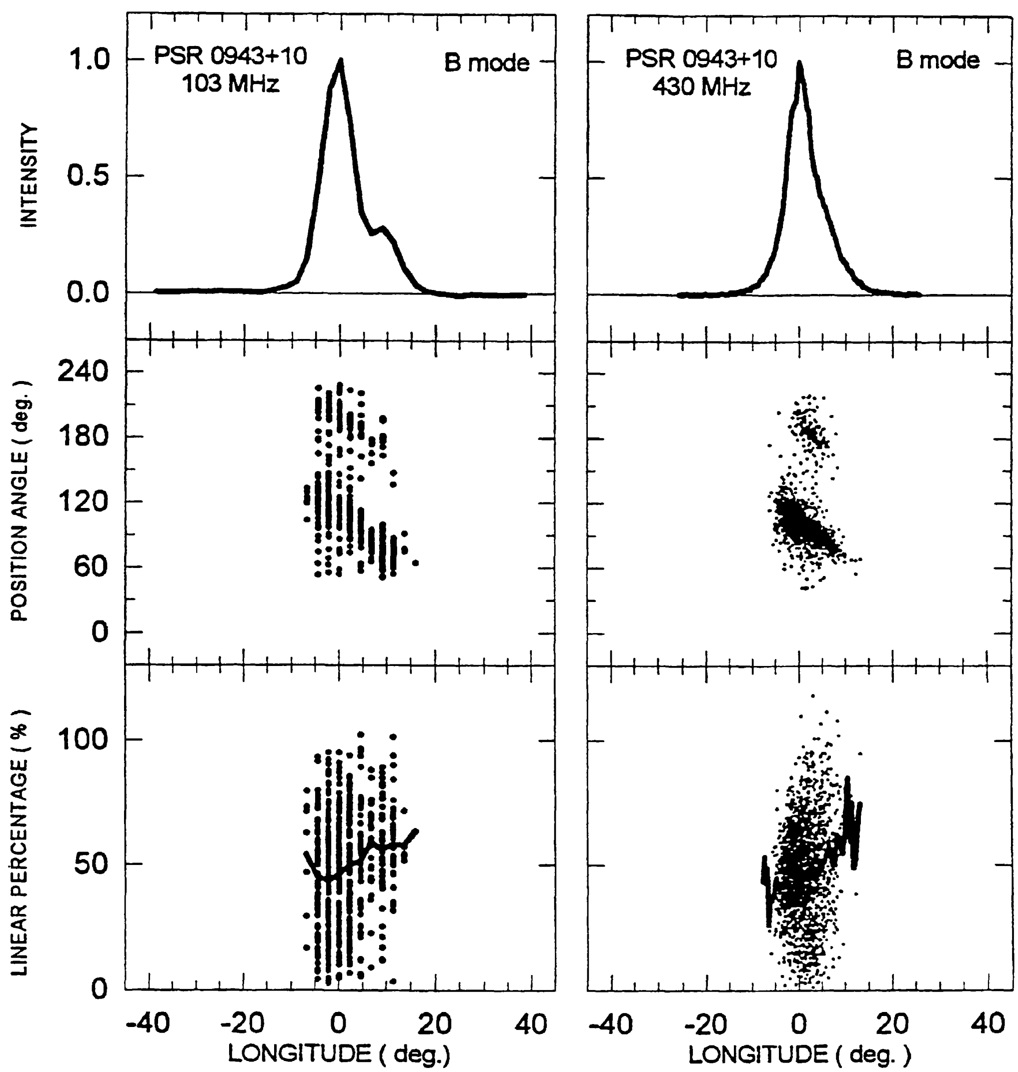

Figure 1. Polarisation displays for PSR 0943+10 in the B-mode profile at 103 MHz (left panels) and at 430 MHz (right panels). The integrated-intensity profiles (Stokes parameter I) are given in the top panels, the linear polarisation-angle histograms in the centre panels, and fractional linear-polarisation histograms along with their average value ($\langle L/I \rangle$) in the bottom panels. The 103-MHz displays are computed from 264 individual pulses recorded at Pushchino Observatory on the 27th December 1990, and those at 430 MHz from 817 pulses recorded using the Arecibo Observatory on the 19th October 1992. The profile peak intensities in the top panels have been normalized to unity, and the 430-MHz PAs rotated by about 90° so as to be easily compared with those at the lower frequency.

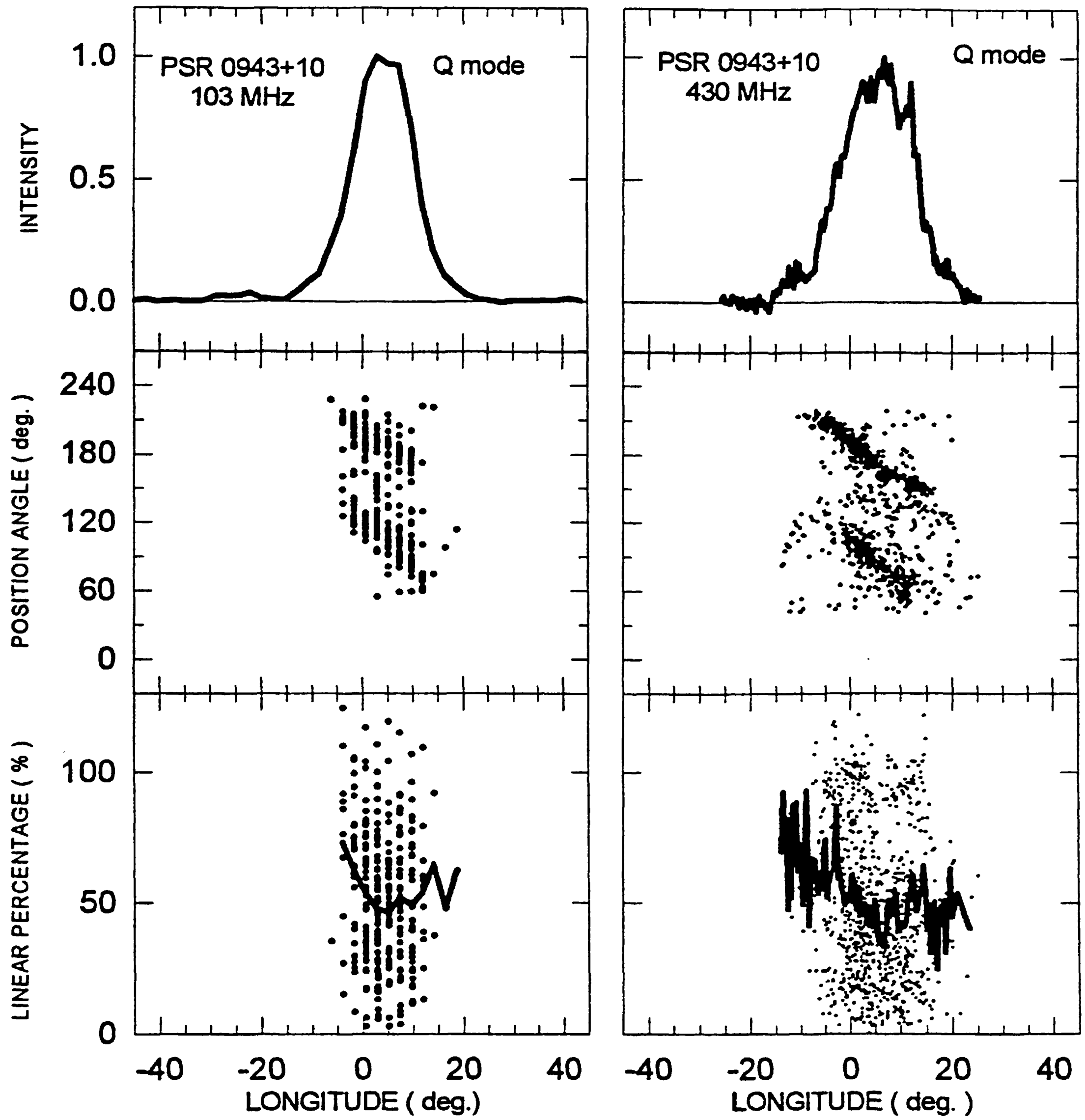

Figure 2. Polarisation displays for PSR 0943+10 in the Q mode as in Fig. 1. The 103-MHz displays are computed from 224 pulses recorded at the Pushchino Observatory on the 28th December 1990 and aligned in time according to the longitude scale in Fig. 1; the 430-MHz displays represent the last 100 pulses of the sequence recorded using the Arecibo Observatory as above.

respectively. Corresponding right-hand panels give the same information for 430 MHz.

The top-left panel of Fig. 1 shows the two-component profile characteristic of the B mode at 103 MHz and below. Its centre panel gives the PA histogram, and individual samples dominated by the primary (PPM) and secondary polarisation modes (SPM) are in clear evidence and form two bands of PA sweep in longitude, typically separated by about 90°. Most B-mode longitude samples are dominated by the PPM; the overlapping of symbols makes this slightly difficult to see in Fig. 1, but some 70% of the points fall in the lower (PPM) band, whose PA sweeps from some 120 to 60°. Note further that the two polarisation modes have different distributions

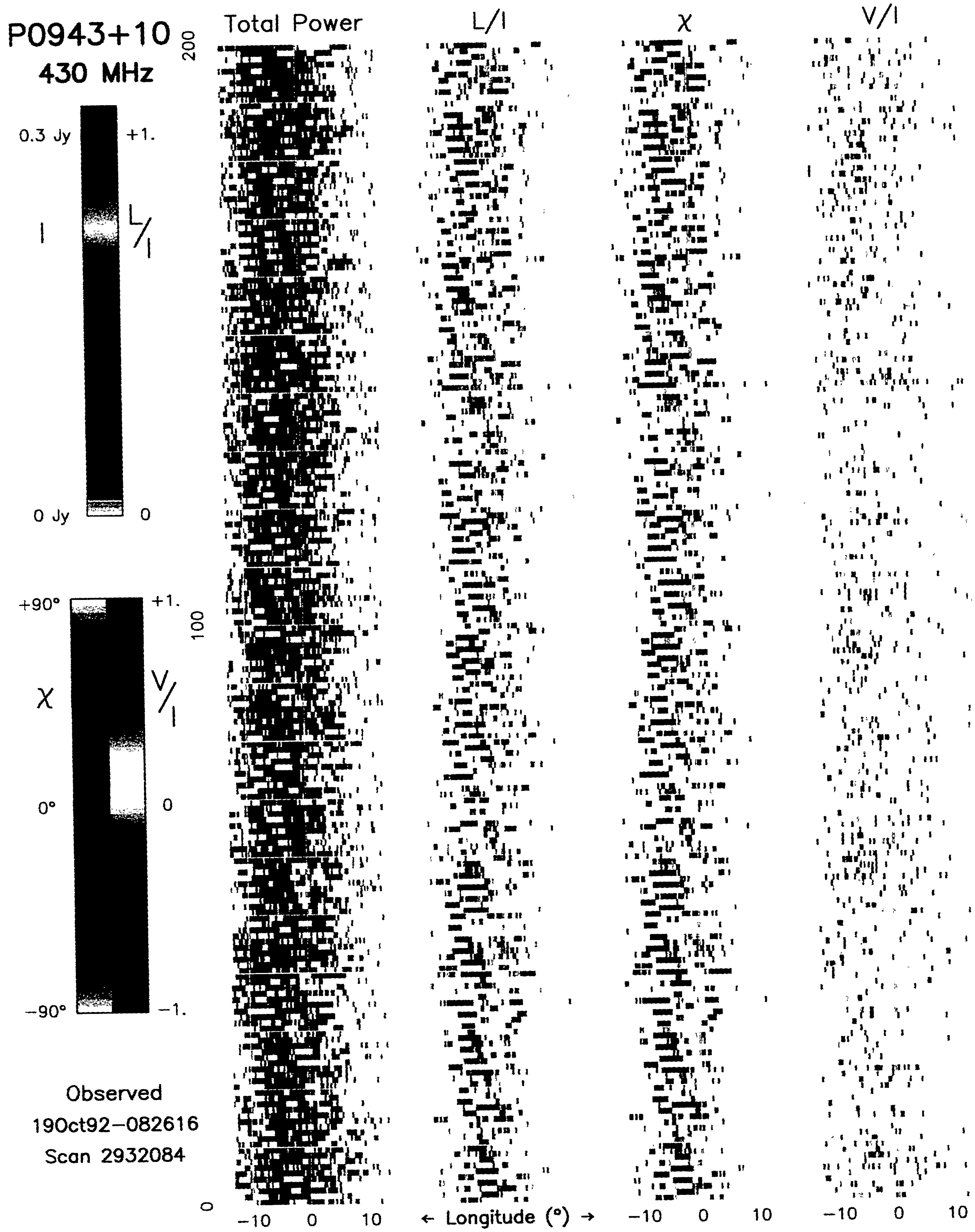
P0943+10
430 MHz
0.3 Jy
+1.
I
L/I
0 Jy
0
+90°
+1.
χ
V/I
0°
0
−90°
−1.
Observed
19Oct92−082616
Scan 2932084
Total Power
L/I
χ
V/I
200
100
0
−10
0
10
← Longitude (°) →

Figure 3(a).

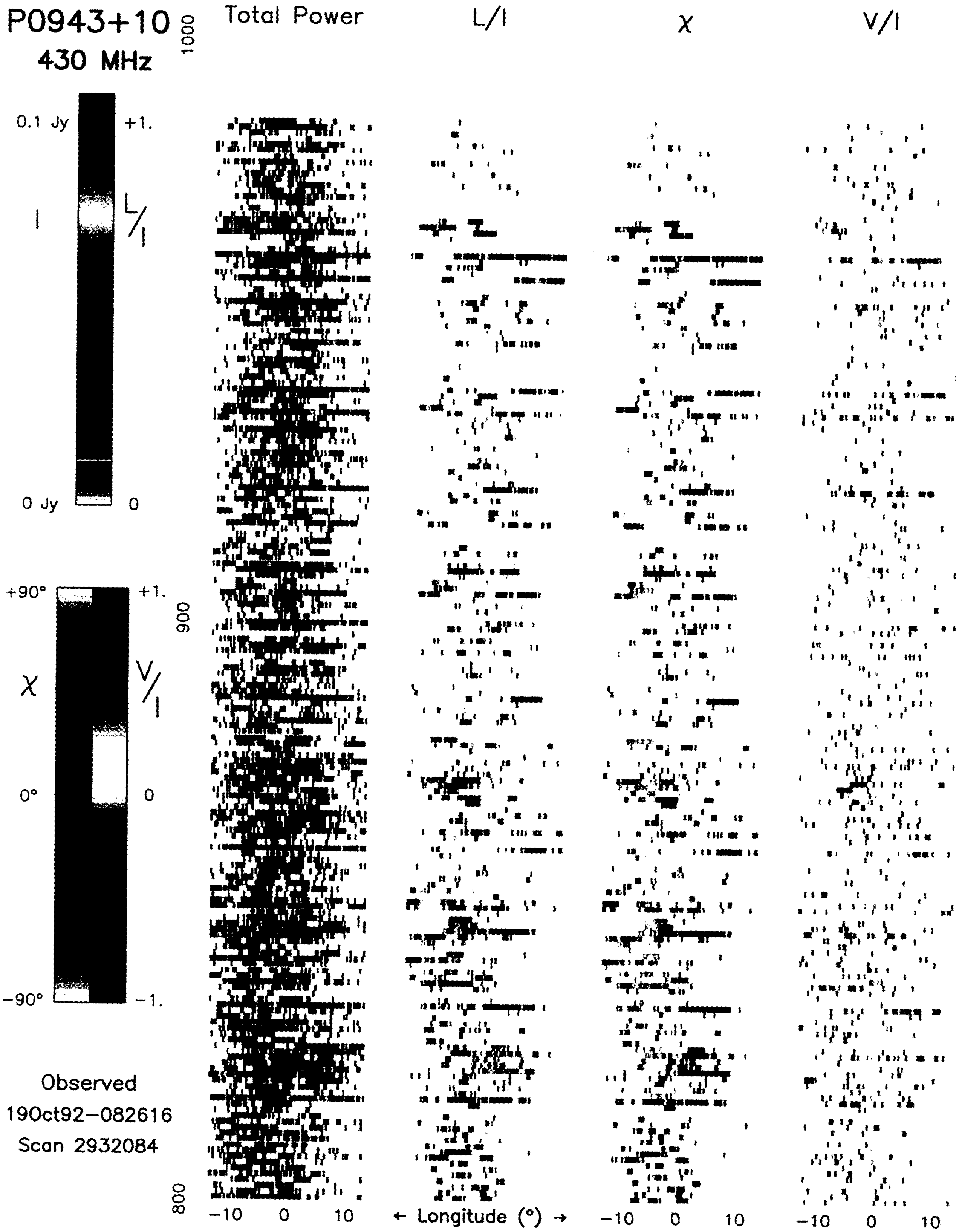
P0943+10
430 MHz
Total Power
L/I
χ
V/I
0.1 Jy
+1.
I
L/I
0 Jy
0
+90°
+1.
χ
V/I
0°
0
−90°
−1.
Observed
19Oct92−082616
Scan 2932084
1000
900
800
−10
0
10
← Longitude (°) →
−10
0
10
−10
0
10

Figure 3(b).

over the pulse window. PPM-dominated samples span the entire window, whereas SPM samples are found primarily under the main component. Clearly, the SPM becomes considerably weaker at longitudes corresponding to the second component. The PA sweep rate, computed over the entire band at 103 MHz is about 3.4° per degree of longitude.

The bottom-left panel of Fig. 1 gives the fractional linear polarisation associated with each B-mode longitude sample at 103 MHz. Values range fully from nearly complete to almost zero polarisation, suggesting that the time scale for polarisation-mode mixing is comparable to the sample interval. The aggregate linear polarisation varies between about 40 and 60% and shows some tendency to increase under the extreme outer edges of the profile.

The left-hand panels of Fig. 2 give similar information for the Q-mode profile at 103 MHz. Note that the profile is not only unimodal in form, but that its peak falls much later than that of the B-mode profile in Fig. 1. The PA distributions (centre panel) of the primary (lower) and secondary (upper) bands are here more nearly similar. They both span the entire longitude range under the pulse window, and the sample PAs are almost equally distributed between the two polarisation-mode bands. About 46 and 54% of the samples are PPM and SPM dominated, respectively. The fractional linear polarisation of the samples again varies greatly, from zero to essentially 100%, with longitude-averaged values again falling between 40 and 60% within the window, just as did the B mode above. The different frequencies of occurrence of the PPM and SPM in the B and Q modes result, however, in significantly different levels of fractional linear polarisation in the modal profiles, 25% in the B mode and 15% in the Q mode.

Turning now to the Arecibo observation, the 18-minute or 986-pulse, fully polarimetric sequence recorded at 430 MHz in October 1992 was perhaps the longest such observation ever made of this pulsar. Fortunately, during this sequence a transition from the B mode to the Q mode was observed for the first time. Of the 986 recorded pulses, the first 817 clearly represent the B mode. We see this immediately from colour displays such as those in Fig. 3, wherein the normal, regular drifting-subpulse behaviour associated with the B mode is obvious (Fig. 3(a) gives a purely B-mode sequence comprised of pulses 1–200). Fig. 3(b), however, shows pulses 801–986 of the sequence in which the transition from the B mode to the Q mode occurs. An abrupt, dramatic change in the properties and organization of the subpulses begins with the 818th pulse, and we see that the final 169 pulses of the sequence correspond

Figure 3(a) & 3(b). Colour dislays of 200-pulse sequences of the 430-MHz observations in Figs. 1 and 2, (**a**) a B-mode sequence comprised of pulses 1–200 of the 19th October 1992 Arecibo observation, and (**b**) the transition region from B-mode to Q-mode emission comprised of pulses 801–986—note the abrupt change in properties at about pulse 817. The first column of the displays gives the total intensity (Stokes parameter I), with the vertical axis representing pulse number and the horizontal axis pulse longitude (a range encompassing the entire emission window is shown here), colour-coded according to the left-hand scale of the top bar to the left of the displays. The second and third columns give the corresponding fractional linear polarisation ($L/I = \sqrt{Q^2 + U^2/I}$) and its angle ($\chi = \frac{1}{2}\tan^{-1} U/Q$), according to the scales at the top-right and bottom-left of the left-most panel. The last column gives the fractional circular polarisation (V/I), according to the scale at the bottom-right of the left-hand panel. No rotation has been applied to the PAs; therefore, their values are nearly orthogonal to those in Figs. 1 and 2.

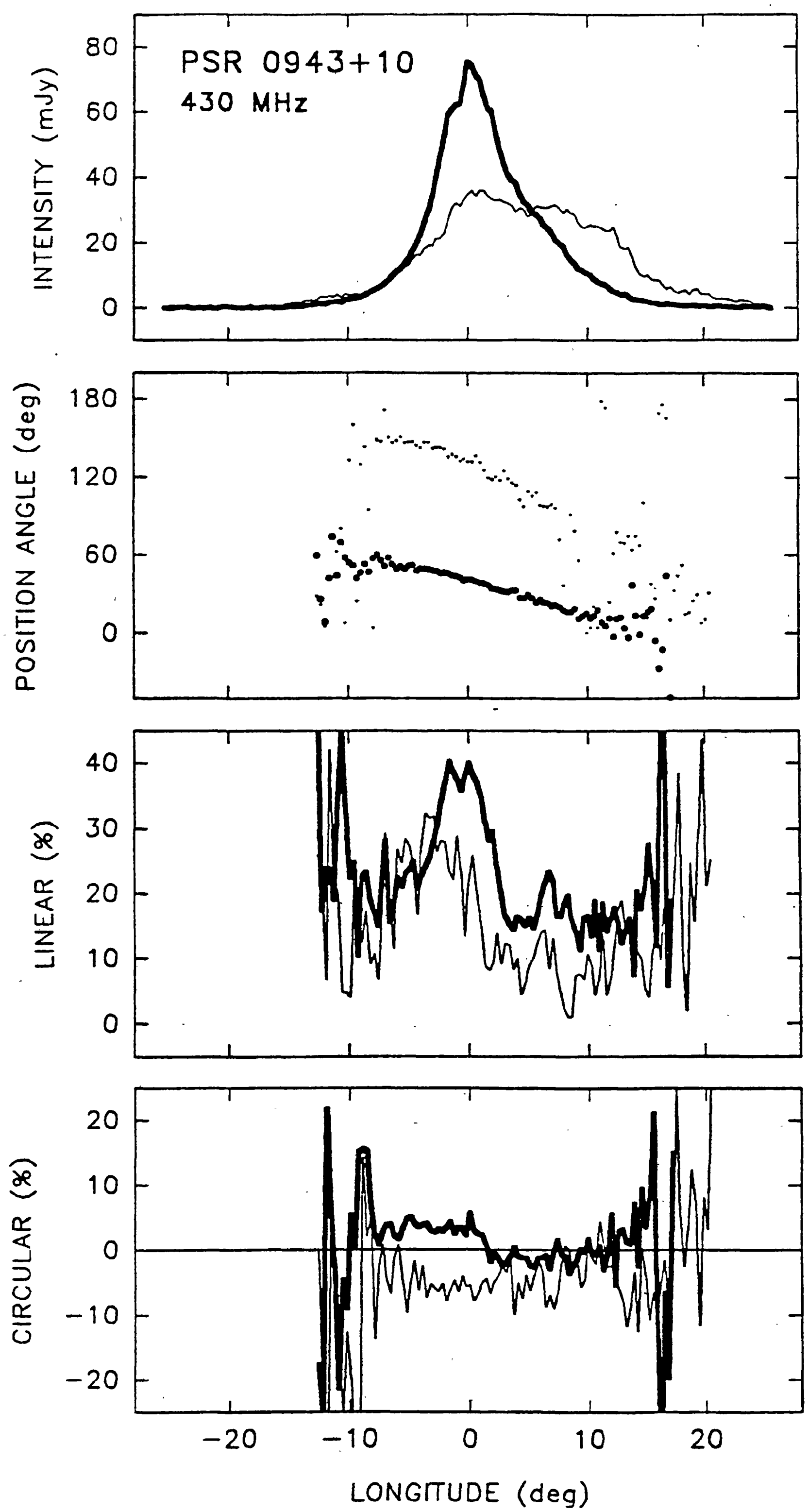

Figure 4. Average-polarisation characteristics of the pulse sequences identified as belonging to the B mode (thicker curves) and Q mode (thinner curves) at 430 MHz. Panels giving the total intensity, polarisation angle, fractional linear, and fractional circular polarisation are shown (defined as in Fig. 3). The peak intensities are not normalized. About 40° has been added to the PAs for ease of display.

Table 2. Characteristics of individual pulses.

	102.5 MHz		430 MHz	
	B mode	Q mode	B mode	Q mode
PA sweep rate, °/°	−3.4 ⟨−3.0⟩	−2.7	−2.4 ⟨−3.0⟩	−3.6
Fractional linear	48 ± 1	49 ± 1	47 ± 1	47 ± 1
Occurrence of PPM (number of samples)	808	235	5371	392
Occurrence of SPM	370	272	576	562

to the pulsar's Q mode. Here, the drifting-subpulse modulation characteristic of the B mode ceases entirely, and the Q-mode emission extends to much later longitudes than does that of the B mode.

Figure 4 gives average profiles computed from the 817 B-mode (heavy lines) and 169 Q-mode (lighter lines) pulses. The intensities are normalized by the numbers of pulses included in each, and thus the profiles clearly demonstrate the weaker, but broader overall character of the Q-mode profile. Note carefully how far the Q-mode emission extends in longitude: some subpulses are visible even at a longitude of 20° and significant emission is seen near longitude −12°.

The rotation of the average PA is shown in the second panel of Fig. 4, and the PA tracks corresponding to the B and Q modes are interesting. Both are comprised of differing contributions of PPM and SPM power. The B mode is dominated by the former and the Q mode by the latter, and this leads to average-PA tracks which are only roughly orthogonal. Note that the separation between the two tracks differs significantly from 90°. As summarized in Table 2, the different values of PA sweep rate corresponding to the B and Q modes combine to yield the average value of 3°/° characteristic of the total profiles at either frequency.

The fractional linear and circular polarisation are given in the bottom panels of the figure. The more comparable contributions of PPM and SPM power in the Q mode cause it to be more severely depolarised. The fractional linear polarisation of the B mode exhibits two minima at the edges of the main component, which are also observed in individual subpulses and correlate with ~ 90° PA "jumps" at these longitudes. The aggregate circular polarisation of the two modes is quite modest and has opposite senses in the two modes.

We can then carry out the same modal analysis of individual-pulse polarisation on the 430-MHz sequence as for the 103-MHz observation above. The results of this exercise are shown in the right-hand panels of Figs. 1 and 2. Virtually every comment which was made about the 103-MHz observations can now be said of the 430-MHz ones.

Note the asymmetric, hardly double form of the B-mode profile in the top-right panel of Fig. 1 in contrast to the weak, broad, delayed form of the Q-mode profile in the corresponding position of Fig. 2. The B-mode PA distribution in the centre-right panel of Fig. 1 is again dominated by the PPM (90% of the samples), which is active over the full width of the profile, in contrast to the more limited longitude range of SPM activity; and in the corresponding Q-mode distribution in Fig. 2, the situation is reversed with SPM-dominated samples both predominating (59%) and occurring over a larger range of longitude. As a result the aggregate fractional linear polarisation is again weaker in the Q mode (14%) relative to the B mode (27%), just as at 103 MHz.

Overall, we see that the B- and Q-mode profiles, their polarisation properties, and their fluctuation characteristics, are very similar between 430 and 103 MHz. Hence we have every indication that pulse 818 in the 430-MHz sequence represents a clear and abrupt cessation of B-mode activity and a commencement of Q-mode emission.

4. Abrupt and slow changes accompanying the modal transition

Average profiles constructed from short subsets of the entire sequence further demonstrate the analogy with the B and Q modes identified at 103 MHz. The redistribution of power within the average-profile window is most evident over the

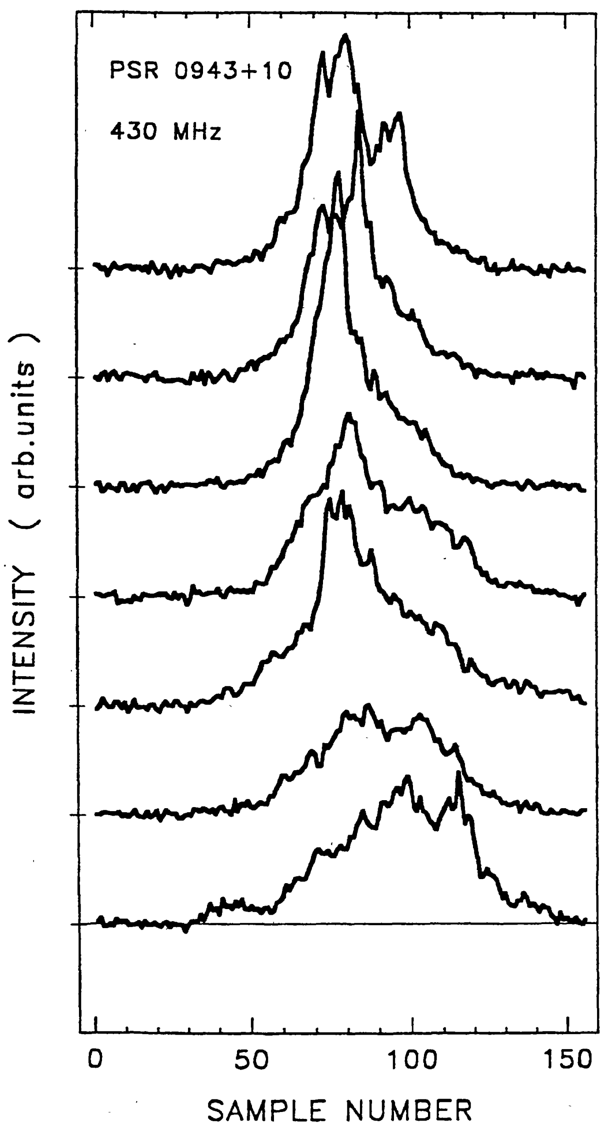

Figure 5. A sequence of integrated, total-power profiles, calculated by averaging over 50 consecutive pulses (top: #s 637–686, and bottom #s 937–986). The middle profile (#s 787–836) includes 30 pulses before, and 20 pulses after, the mode change. The peak intensities have not been normalized relative to each other. The B-mode profile peak falls at sample 78, and the sample interval is 0.33°.

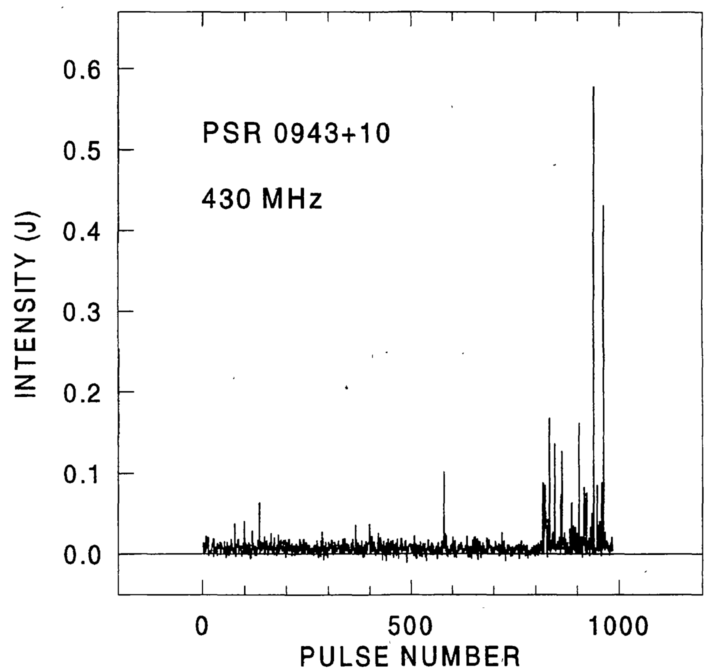

Figure 6. Intensity versus pulse number in a narrow longitude window near on the trailing edge of the B-mode profile (samples #s 112–114, 11.5 ± 0.5°) for the 986 pulses of the 430-MHz observation.

last 350 pulses of the 430-MHz observation. Fig. 5 shows the result of consecutive 50-pulse integrations within this interval. Overall, it is clear that the transition from the B to the Q mode entails decreasing activity in the leading part of the profile and enhanced power emitted on the extreme trailing edge of the profile. The decrease in the average intensity of emission under the leading part of the profile is particularly marked in the last two subaverages. The profile corresponding to these last hundred pulses was shown in the top-right panel of Fig. 2 and closely resembles the 103-MHz Q-mode profile adjacent to it. Specifically, the overall shapes of these last several subaverages are more nearly that of a broad, weak, single component, whose centre is appreciably delayed relative to the B-mode profiles; if there are separate components within this overall form, they are not resolved.

The enormous intensity of certain individual pulses during intervals of Q-mode emission is evident in Fig. 6, where the power in a narrow window near the trailing edge of the Q-mode profile at about 11.5° is plotted against pulse number for all 986 pulses of the observation. Strong emission in this region of the pulse window is highly unusual in B-mode sequences, but *some* pulses are *remarkably* bright at this longitude after the transition to the Q mode. Note, however, that of the nearly 170 pulses after the mode change, no more than 20 or so are extraordinarily bright—and many of these only over limited ranges of longitude (see Fig. 3(b)). So, while the pulsar's emission is weaker in its Q mode, it is hardly quiescent!

Finally, we come to the most interesting aspect of our investigation of 0943+10's mode-switching phenomenon. Fig. 7 gives the intensity in three windows, averaged over successive groups of 10 pulses, resulting in 98 such averages in all. The "A" window is taken near the B-mode peak at about 0 ± 1.7° longitude (samples 73–83, see Fig. 5), the "B" window near the centre of the Q-mode profile at about 6.6 ± 1.7°

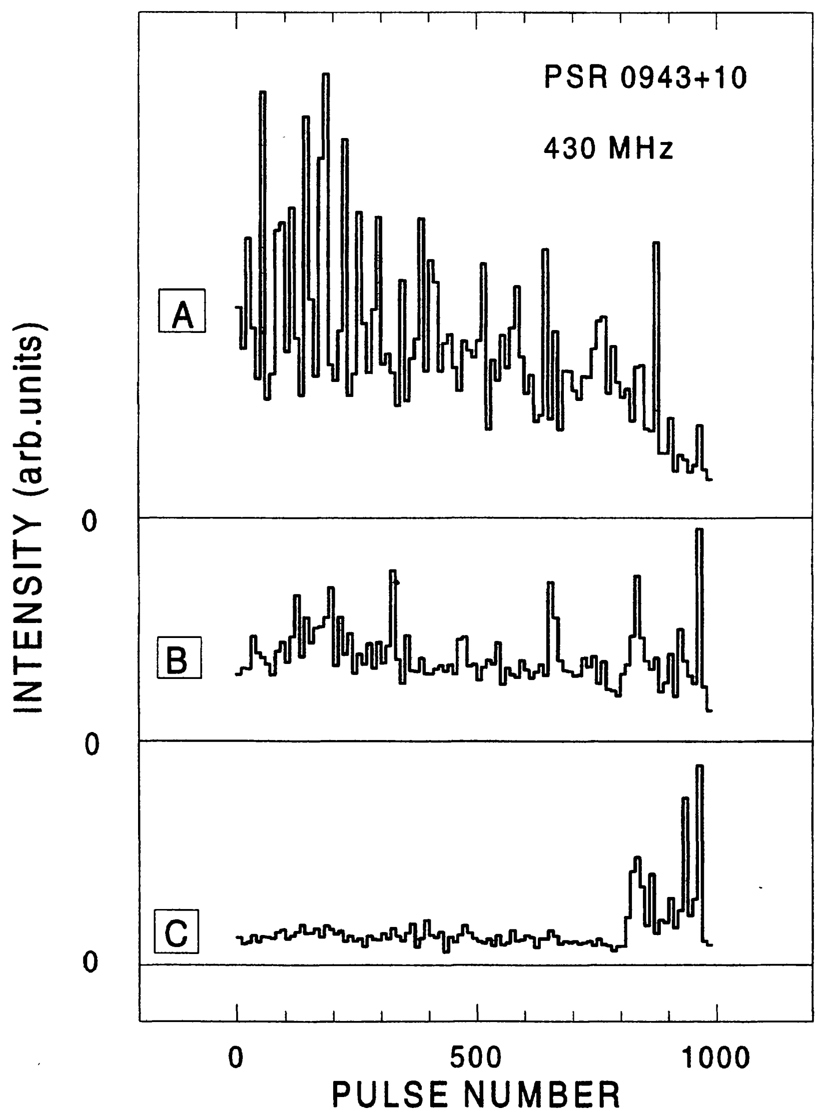

Figure 7. Secular variations in the intensity of PSR 0943+10 in three longitude windows at 430 MHz: **A**: (samples 73–83, $0 \pm 1.8°$), **B**: (93–103, $6.6 \pm 1.8°$) and **C**: (108–118, $11.5 \pm 1.8°$). Each value represents the average over 10 consecutive pulses for a total of 98 integrations. The mode change falls near the middle of the 82nd average as is seen clearly by the suddenly enhanced intensity in window C. Note that the power in window A slowly declines, while that in window B remains relatively constant.

(samples 93–103), and the "C" window just before the trailing edge of the Q-mode emission at about $11.5 \pm 1.7°$ (samples 108–118).[5]

The transition from B-mode to Q-mode emission falls near the middle of the 82nd average, and indeed, a sharp rise in intensity is seen in the C window (see also Fig. 6), pointing to the fact that the modal transition has a time scale as short as a pulsar period, as is observed for other "mode switching" pulsars. Rather little intensity change is seen in the B window near the peak of the Q-mode

[5] These windows were defined by a fitting procedure: a combination of three Gaussian-shaped components, centred at fixed longitudes, describes both the B- and Q-mode profiles rather closely.

profile[6]—however, this point also corresponds to the mid-trailing edge of the B-mode profile (see Fig. 4, top panel).

What is arresting, however, is the behaviour of the A-window intensity. Here we see that its intensity falls gradually throughout the entire interval prior to the transition point, and then more rapidly following this modal transition. The modal change in A-window intensity is very considerable, but it is not at all abrupt. It appears, therefore, that the switching process in this pulsar involves both rapid and slower changes. This gradual decline of intensity centred on longitudes of enhanced B-mode emission—extending over at least 15 minutes—appears to represent some form of "pre-switching transition process".

5. Frequency dependence of the two modal profiles

Since two distinct modes have been identified at 430 MHz, we can study the evolution of their respective integrated profiles over a wider frequency range. Fig. 8 displays integrated pulse profiles in the B mode (heavy lines) and Q mode (lighter lines) at five frequencies, 25, 40, 61, 103 and 430 MHz. At all but the lowest frequency, the respective profile pairs are time aligned, and at 25 MHz they have been adjusted to span about the same longitude interval.[7]

Several conclusions about the frequency evolution of 0943+10's pulse profile can be summarized as follows:

- The B-mode profile has two resolved components. The spacing between the components increases very rapidly between 25 and 103 MHz. This behaviour can be described by a power law with spacing $\Delta s \sim f^{-0.63\pm0.05}$.
- The relative intensity of the trailing component in the B-mode profile varies hardly at all with frequency in the range between 25 and 103 MHz, and then abruptly falls off between 103 and 430 MHz. This behaviour is reminiscent of the "absorption" phenomena seen in other stars (see Rankin 1983).
- The Q-mode profile has a simple and very similar shape at 61, 103 and 430 MHz. At lower frequencies the profile bifurcates, and the two components become increasingly well resolved below 40 MHz.
- The peak of the Q-mode profile occurs some $4.5 \pm 1°$ earlier than the trailing component of the B-mode profile. It is remarkable that this shift is independent of frequency to within the (resolution-limited) accuracy of our measurements. It is worth noting that the 430-MHz windows B and C discussed above are also separated by some 4.9°; window C probably locates the (vestigial) B-mode trailing component, which becomes active in the Q-mode profile.

[6] While the relatively constant B-window intensity mitigates against diffractive-scintillation-induced intensity variations, we also note that our 10-MHz passband would tend to average out any such modulation. Little is known about 0943+10's dynamic spectrum, but its measured proper motion (Lyne *et al.* 1982) suggests a velocity as large as 200 km/s. On this basis, its scintillation bandwidth at 430 MHz is probably well less than one MHz (see Cordes 1986).

[7] The two distinct modal profiles measured by Phillips & Wolszczan (1989) at 25 MHz were arbitrary aligned in their paper so that "the peak of the trailing component in each profile had the same pulse phase". Our alignment (although still arbitrary) reflects the observed alignment at higher frequencies (except 430 MHz), where the modes span about the same longitude interval.

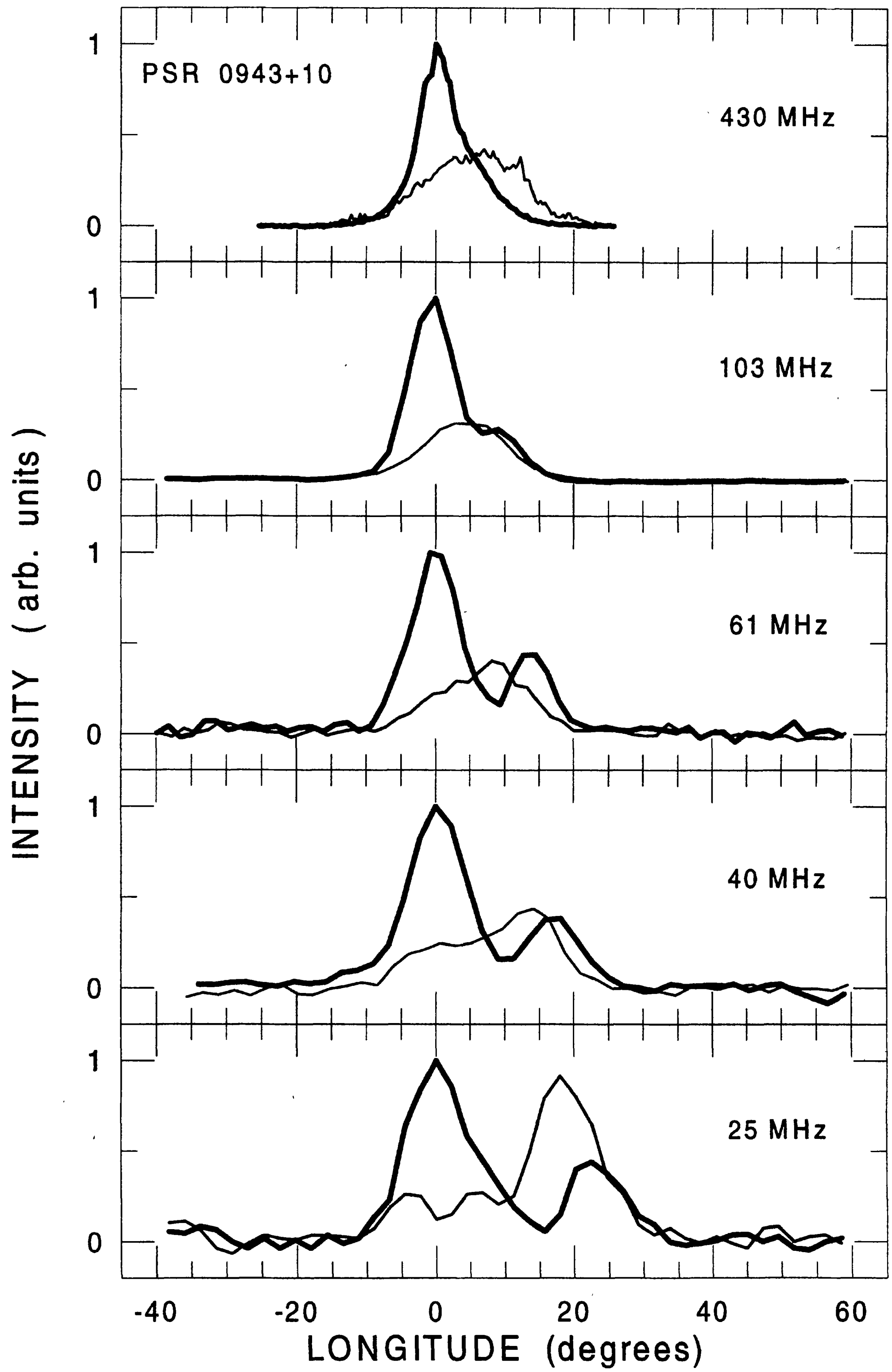

Figure 8. Evolution of the integrated pulse profile of pulsar 0943+10 in the B mode (heavy lines) and in the Q mode (lighter lines) with frequency. Each profile is normalized to its peak value in the B mode. The five profiles have been shifted in longitude so as to position their B-mode peaks at the longitude origin. The 40 and 103-MHz modal profiles were obtained during simultaneous observations on 27th and 28th December 1990, respectively.

- Generally, the integrated pulse profile of PSR 0943+10 has three components: components A and C form the double profile characteristic of the B mode, while central component B usually dominates in the Q-mode profile. The intensities of components A and C decrease, but do not vanish, during Q-mode sequences. Similarly, the intensity of component B seems to determine the amplitude level in the saddle region of the B-mode profile.

6. Summary and discussion

Two modes of subpulse organization are identified in an 18-minute pulse sequence at 430 MHz, and their properties correspond closely to the well known B and Q modes at 103 MHz. The B-mode sequence at 430-MHz is comprised of a highly regular, relatively intense pattern of drifting subpulses which is confined to the first half or two-thirds of the overall window of emission; whereas the Q mode entails a disorganized splatter of mostly weak subpulses, punctuated by a few extraordinarily bright ones, emitted over a broader longitude range, both earlier and particularly later than that of the B mode.

The polarisation behaviour is also similar to that observed at 103 MHz: the B mode exhibits a great preponderance of primary polarisation-mode emission (and the little SPM emission is confined to a narrow region of longitude close to and just following the average-profile peak) and thus remains relatively highly polarised in the average; whereas the Q mode shows only a slight excess of secondary polarisation-mode emission and thus is largely depolarised in the average. That the B-mode average profile exhibits a maximum fractional linear polarisation of no more than about 40% argues that significant mode mixing is occurring on scales smaller than the 1-ms sample interval. The integrated profiles also exhibit small amounts of circular polarisation over the first half or so of the emission window; left-hand (positive) circular polarisation is associated with the B mode, and right-hand (negative) with the Q mode.

We find that the process of transition from the B mode to the Q mode is more complicated in PSR 0943+10 than for most other pulsars which exhibit the mode-changing phenomenon. While the overall organization of the subpulses "switches" abruptly at the B-mode/Q-mode boundary, it appears that other, slower changes, accompany this overall reorganization of the emission. Indeed, we find that the intensity of the main B-mode component declines progressively before the "switch" and more rapidly just following it. We know of only one other pulsar, 0355+54, in which there is also some evidence of slower changes concommitant with the sudden reorganization of emission which a "mode change" represents (Morris *et al.* 1980).

A clear example of the switching process from the Q mode to the B mode at 40 MHz has been given by Suleymanova *et al.* (1996), which is something of the inverse of the B-mode-to-Q-mode "switch" that we have observed at 430 MHz. Accounting for the broad-band character of the mode-switching process, the complete scenario of mode switching at 430 MHz seems to be as follows: the onset of the B-mode sequence (which preceeded the beginning of our observation by some minutes) probably also occurred abruptly, via the re-establishment of bright, organized, drifting-subpulse emission within the longitude interval of the main component. This emission then slowly relaxes, as we have seen, with gradually decreasing pulse intensity on a time scale of 1000 or more pulse periods. Then, at some later time, the electrostatic conditions in the polar-cap region can no longer sustain the intensive, organized subpulse emission, and it degenerates into a much weaker, more chaotic condition (punctuated by occasional extraordinarily bright individual subpulses) until conditions are again favourable for a renewed cycle of bright, organized emission.

We hope that in time it will be possible to understand the physical causes of these gradual and abrupt changes associated with the "mode changing" phenomenon, but as yet we know of no reliable theoretical structure into which they can be accommodated.

Acknowledgements

It is a pleasure to thank Amy Carlow and Kyriaki Xilouris for help with the 1992 observing, Phil Perillat for his remarkable software for the Arecibo 40-MHz Correlator, and Slava Pugachev for assistance in developing the programs used in the observations and analysis at 103 MHz. This work was supported in part by grants from the U. S. National Science Foundation (AST 89-17722 and INT 93-21974). Arecibo Observatory is operated by Cornell University under contract to the U. S. National Science Foundation.

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