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Polar-Fluxtube Emission 'Weather' of Pulsar B0943+10: Polarisation, Modes, & Theoretical Implications[1]

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Abstract. Building on the analysis of the previous paper by one of us, we here turn first to a discussion of B0943+10's chaotic "Q" mode and then to the polarisation properties of its "B"-mode radiation. Here again, we see evidence that the plasma processes responsible for pulsar emission may be organized into a system of columns. In short, 0943+10 provides unprecedented insight into the phenomena comprising what might be termed pulsar polar-fluxtube "weather".

The 0943+10 "Q"-Mode Pulse Sequence

Here, as in Bonn, this paper follows directly upon the foregoing one, Deshpande's invited talk, which treats the techniques that we have developed to study pulsar B0943+10's exquisitely stable "B" mode. Both his discussion and this one are pursued in much more detail in Deshpande & Rankin (1999, 2000).

Indeed, just before stopping, Desh began to show a "movie" of this pulsar's subbeam pattern, constructed from short segments of the 1992 Arecibo sequence—and this "movie" can be downloaded using Netscape from either http://www.rri.res.in/~desh or http://www.uvm.edu/~jmrankin. The foregoing paper considered the first 816 ("B"-mode) pulses of the sequence, but the last 170 pulses are in the "Q"-mode. Still images of the pulsar's subbeam pattern after pulse 816 are completely inadequate to show the dramatic changes, so we encourage readers to view the "movie" several times before reading further.

Fig. 1a shows the chaotic subpulse behavior of the 170-pulse "Q"-mode sequence as well as the broader average profile first studied by Suleymanova *et al* (1998). Fluctuation-spectral study of this short sequence (Deshpande & Rankin 2000) provides evidence that the circulation time varies little across the modal boundary, and so we were emboldened to construct polar maps of the "Q"-mode sequence using the 37.3-P_1 value of $\hat{P}_3$ determined for the "B" mode.

Remembering that the subbeam maps (including the movies) depict the pattern in the frame of their 37.3-P_1 rotation—and that new information about

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[1] This paper also includes the poster presentation entitled: "Pulse-Sequence Cartography of Conal-Single Pulsars" by Deshpande & Rankin

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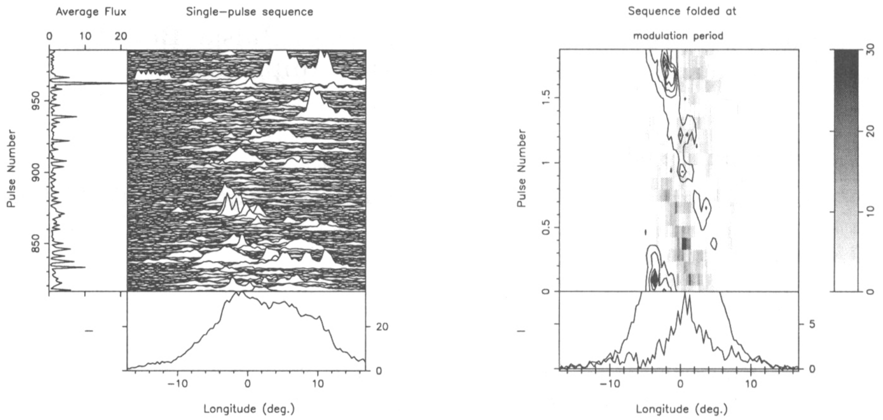

Figure 1. a) Chaotic individual-pulse behaviour during the 1992 "Q"-mode sequence (pulses 817–986). The average profile is shown in the bottom panel and the pulse-energy variation in the left-hand panel. Note the extremely intense subpulses and the enhanced emission on the trailing edge of the window as compared with the "B" mode. b) Block-averaged pulse sequences computed from respective PPM (contours) and SPM (grey scale) partial sequences. The PPM and SPM "drift" along parallel "tracks" within the 1.87-P_1 phase-modulation cycle.

a particular subbeam is available only when it once again rotates back into our sightline—note the dramatic changes which begin with pulse 817. At the onset of the "Q" mode, most of the subbeams are weak but still distinguishable; however, first one and then two are exceptionally strong, with their intense discharges filling the area around them and spilling into larger radii or heights. Their lifetimes appear shorter than P_1, not allowing adequate sampling, thus resulting in their "streaky" character. These dramatic "Q"-mode events do not entirely displace the old ("B"-mode) subbeams, which crowd together, leaving space in the ring where new subbeams can appear. In the process, more subbeams are created, whose configuration is necessarily more compact, which then leads to faster fluctuations. Groups of closely spaced subbeams are evident, with spacings which correspond to the observed 0.77 c/P_1 feature. Large intervals of weak activity in fact seem to prompt the intense discharges, but eventually the closely spaced subbeams adjust themselves in number so as to have enough space for themselves—thus reestablishing the conditions for the bright and steady configuration that characterizes the "B"-mode sequences.

Polarisation of 0943+10's Subbeam Radiation

We have computed partial sequences corresponding to the primary and secondary polarisation modes (PPM and SPM) as well as the unpolarised power (UP), and these provide ideal instruments for studying the polarisation be-

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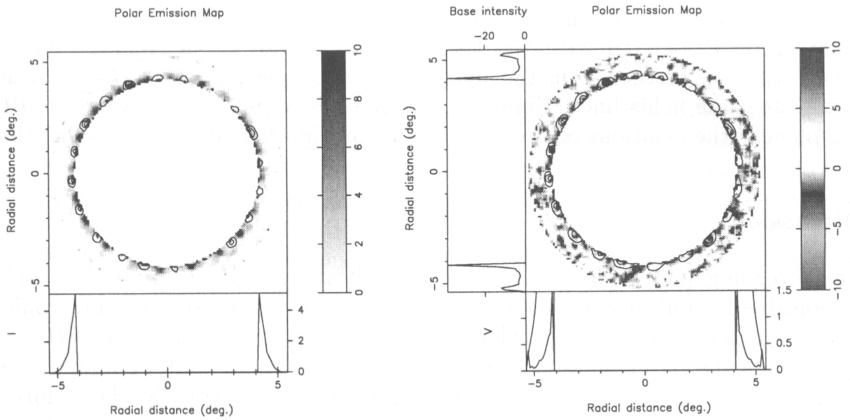

Figure 2. Polarised polar maps: a) The PPM is shown as a set of contours and the SPM as levels of grey. The scales of the two modes are not equal, the weaker SPM having been enhanced so as to be approximately as prominent as the PPM. Note that the SPM power falls between the PPM subbeams. b) Stokes I is shown as a set of contours and Stokes V as a colour plot. Note that the PPM-dominated I subbeams are LHC polarised, whereas the SPM-associated region between them is RHC polarised. Each of these circularly polarised regions has a tendency to extend to "outside" regions, which may be indicative of higher altitudes in the emission region.

haviour (Deshpande & Rankin 2000; see Appendix). First, each of these sequences can be folded at the basic 1.87-P_1 phase-modulation cycle (P_3). Figure 1b then depicts the behaviour of the PPM- and SPM-associated modulation. We see that the PPM and SPM tracks are parallel as expected, though we could not have anticipated that the latter would fall almost exactly in between the former, so that PPM and SPM subpulse "tracks" will always be found at a longitude interval of $P_2/2$ or some 5.3°.

Of course, each of these sequences can also be mapped onto the polar cap using the cartographic transform, and the relation between the PPM and SPM beams is shown in Figure 2a. Note that the SPM emission also forms a set of subbeams along nearly the same circle as that of the PPM. Indeed, we know that all these subbeams rotate ccw about the magnetic axis at the centre of the diagram and that the star's overall cw motion about its rotation axis (at the top of the diagrams) causes the sightline path to traverse from right to left through the beams, just poleward of the magnetic axis. The different longitude centres and modulation phase of the SPM and PPM power together determine the relative (azimuth) orientation of their respective subbeam systems.

Finally, we can locate the circular polarisation within the "drift" bands and within the subbeam system in a similar fashion. Positive (LHC) circular polarisation is associated with the total power, which in turn is dominated by the PPM emission; whereas negative (RHC) circular polarisation is associated

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with the SPM. Figure 2b gives a polar map wherein the total power is shown as a set of contours and the circular V as a colour scale. Here also, we see LHC polarisation associated with the PPM beams as well as the region "outside" them—that is, further from the magnetic axis or perhaps at greater altitudes along the same fields lines. Similarly, the RHC is found just between the PPM beams near the positions of the SPM beams in Fig. 2a and also "outside" them.

Discussion

The foregoing paper has discussed the implication that the particle currents responsible for pulsar emission break up into a fairly discrete columnar configuration, having "feet" in the acceleration (polar cap?) region and then extending up through the radio emission region to such large height that we may conceive of them as continuing to or beyond the light cylinder. Electrically, these emission columns carry at least one side of the "circuit" which powers the star's emission by tapping the energy of its spindown "battery".

The plasma flow within the columns is guided by the dipolar magnetic field only out to some critical distance $r_{\rm crit}$—which nonetheless is at a greater height than the radio emission region—and probably at a height where the toroidal field components produced by the particle currents begin to become important. The lower level of organization observed in the higher altitude 34-MHz pattern (Asgekar & Deshpande, this volume), compared to that in our 430- and 111.5-MHz observations, may reflect this circumstance. In any case, such a picture is very close to that envisioned by Goldreich & Julian (1969).

We can crudely estimate $r_{\rm crit}$ by assuming that each emission column carries 1/40-th of the spindown energy and then computing the height at which the energy density of the column $\mathcal{L}_{\rm beam}/\pi r_{\rm col}^2 c$ equals that of the magnetic field $B^2/8\pi$. The former is about $2.8{\times}10^{13}(r/r_*)^{-n}$ ergs/cm^3; whereas the latter is some $1.6{\times}10^{23}(r/r_*)^{-6}$ ergs/cm^3. If the columns expand with the field (n=3), then these are equal at a height of $r \sim 1800r_*$—about $r_{lc}/3$, where the energy density would be 4,800 ergs/cm^3. However, if the cascade confines this expansion (n=2?), then r/r_* is ~280, where the energy density is about $4{\times}10^8$ ergs/s.

Polarisation Modes. Figures 2a and 2b provide the first comprehensive view of the polarisation structure of a pulsar beam. We see most of the power of the 20-fold subbeam system being comprised of PPM emission, with the SPM emission falling in between the PPM beams. Moreover, the RHC polarisation is associated with the PPM and the SPM/LHC with a wide region outside and around it. What are we to make of these results?

First, as regards the linear polarisation, we should not think of the PPM power primarily at one angle and the SPM at another. The PPM and SPM in 0943+10 are highly orthogonal, and so their power will almost always add incoherently in such a way that the combined power is depolarised and *carries the PA of the stronger mode.* This implies that the positions characterized by SPM "beams" are merely those regions where the SPM power dominates that of the PPM. Given the about five-times greater strength of the PPM, it is not surprising that we find the SPM "beams" just where the PPM power is weakest. It may well be, then, that the SPM and PPM power are radiated from very close-by regions (perhaps along the same field lines within the emission column, but at

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somewhat different heights); the only condition, then, required to replicate the observed configuration is that the PPM beamform be somewhat more confined than that of the SPM, so that at large angles to the emission column, the SPM emission comes to dominate that of the PPM.

Second, the circular polarisation clearly marks the PPM subbeams; we see LHC associated with the emission columns and RHC in regions outside them. Overall, the level of circular polarisation is low, but at certain points in the subbeams it can be quite large. Some circular polarisation is produced whenever our sightline makes a small angle with respect to the plane containing the radiating charges' velocity and acceleration. Thus, it might then be a natural consequence of radiation from an emission column with a toroidal field component.

Profile Modes. In Suleymanova *et al* and in our discussion above, we have seen that the "B" mode is characterized by quiescence: steady, orderly subpulse modulation of consistent amplitude and remarkable stability; whereas, the "Q" mode exhibits a brightness bordering on violence: weak overall emission punctuated by exceptionally bright subpulses, disrupted modulation, etc. Specifically, we found evidence that at the "B"-to-"Q" transition: a) the "drift" continues in the sense that the circulation time remains about the same, b) the number of subbeams decreases steadily to only one or two at any given time, so that their "feet" on the polar cap are well separated, c) the remaining columns are both much more intense and have shorter lifetimes, d) the emission from the few remaining subbeams comes from more peripheral field lines and/or possibly greater heights, e) the emission is now dominated by the SPM, and f) the emission is more symmetrical with respect to the longitude of the magnetic axis.

All these changes in the properties of the emission, occurring within a single rotation period of the star, must represent some drastic and (at least for a time) irreversible alteration in the global electrodynamic conditions that produce the steady, patterned "B"-mode radiation. Furthermore, Suleymanova *et al* showed that the "B"-to"Q" transition is anticipated by a slow, steady decline in intensity, which we can see also as a steady decrease in overall subbeam intensity throughout the "B" mode sequence. Although the 1992 sequence is the only one in existence which shows a modal transition in 0943+10, Suleymanova & Izvekova (1984) have shown that the two modes occur with about equal frequencies, and they estimated that each had a typical duration of about half an hour. Whatever could produce so many and such dramatic changes in a sequence, over and over again? In the past we have tended to attribute two profile modes to a pair of "metastable states", but in 0943+10 this characterization is clearly incorrect: the pulsar has one *stable* mode and another highly *unstable* mode, which each seem to persist for several tens of minutes.

We believe that these alternating profile modes in 0943+10 may have a rather simple cause. This pulsar has a nearly aligned geometry, so that the emission columns rise from polar cap (which is always near the rotational axis) and pass through the emission region and "up" to the light cylinder like so many "wires" or strings of pasta, to end far from the star somehow within the ambient interstellar plasma. Every rotation of the star then has the effect of twisting this "bundle" of emission columns—only a little near the pulsar, but ever more so at larger heights. No such bundle can suffer an endless amount of such twisting; and the process of twisting will increase the magnetic-field energy

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of the bundle. Ultimately, the twisting will effectively sever some or many of the emission columns, and the magnetic energy stored in the tightly wound "bundle" will accelerate plasma along some of the remaining emission columns.

The observations seem to support just such a scenario: The steady "B"-mode emission is possible only when the columns have relatively little twist, and all 20 of them are distinct and continuous. However, in half an hour the star rotates some 1600 times, and the twists in its emission-column "bundle" produce large-scale toroidal magnetic-field components which store significant energy and, when they become comparable (at some large height) with the dipolar fields, can give rise to field-line "reconnection". In the "B" mode the pulsar takes some time to twist its field enough that it ruptures; whereas, in the "Q" mode it takes some time to reestablish the order, globally, in its magnetic field configuration that is required for the "B" mode to recommence. The declining power of the "B" mode may result simply from the slight transverse compression that the twisting produces; our sightline is already at the outer edge of this pulsar's beam, and any further slight narrowing of its conal beam will rapidly decrease the power we receive from the pulsar. The larger radial diameter of the "Q"-mode emission may just follow from relaxing this radial compression, and its chaotic character from the severing of plasma flow along certain columns to the light cylinder and from dumping stored magnetic energy back down others.

Throughout these changes we still see evidence that the emission columns circulate with a nearly constant period—it is just that they are fewer and they have shorter lifetimes. Finally, the polarisation changes tend to support such a picture; in the "B" mode our sightline is oriented such that we preferentially receive PPM emission—that is, the emission columns radiate nearly in our direction as they pass by the longitude of the magnetic axis. However, in the chaotic "Q"-mode most the emission-column radiation misses us as the field is both distorted and "thrashing around", so that we tend to see emission far from the axis of the emission columns, which will then preferentially have the linear SPM signature and some negative circular polarisation.

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References

Asgekar, A. & Deshpande, A. A. 1999, in IAU Symp. 177, Pulsar Astronomy—2000 and Beyond, ed. M. Kramer, N. Wex, & R. Wielebinski (San Francisco: ASP), 202, 149

Deshpande, A. A. & Rankin, J. M. 1999, ApJ, 524, 1008

Deshpande, A. A. & Rankin, J. M. 2000, MNRAS, submitted

Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869

Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51

Suleymanova, S. A., & Izvekova, V. A. 1984, Soviet Ast., 28, 32

Suleymanova, S. A., Izvekova, V. A, Rankin, J. M. & Rathnasree, N. 1998, Journal of Astronomy & Astrophysics, 19, 1

https://doi.org/10.1017/S0252921100059327 Published online by Cambridge University Press