Part 3
Studies of Radio Emission

Section A. Single Pulses

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Characteristics of Pulsar Radio Emission at Single-pulse Resolution

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Average profiles, subpulses & micro-structure

Pulsar radio emission shows remarkably rich, but complex behavior in both intensity and polarization when considered on a pulse-to-pulse basis. A large number of pulses, when averaged together, tend to approach & define stable shapes that can be considered as distinct signatures of different pulsars. Such average profiles have shapes ranging from that describable as a simple one-component profile to those suggesting as many as 9 components. The components are understood as resulting from an average of many, often narrower, intities — the subpulses —that appear within the longitude range of a given component. The pulse components are thus *formed* and represent statistically an intensity-weighted average pattern of the radiation received as a function of longitude. The profile mode changes recognized in many pulsars suggest that the emission profile of a given pulsar may have two quasi-stable states, with one (primary) state more probable/brighter than the other (secondary) state. There are also (often associated) polarization modes that represent polarization states that are orthogonal to each other. The complex nature of orthogonal *jumps* observed in polarization position-angle sweeps may be attributable to possible superposition of two profile/polarization modes with orthogonal polarizations.

When viewed at high time-resolution, the emission displays very rich structure at sub-milli-period scales, the so-called micro-structure (*e.g.*, Hankins 1972). The micro-structure shows quasi-periodic patterns that appear correlated over wide frequency ranges. It is not entirely clear yet whether they represent a mere temporal variation in emission or are really the manifestation of some angular (spatial) patterns associated with the radiating regions. The *coherent* nature of the pulsar emission (implied by the high brightness observed) must manifest itself via other signatures and some sort of a diffraction pattern imprint should be evident if coherence across an interesting range of transverse spatial scales is indeed operative (*e.g.*, Ables *et al.* 1997).

The average-pulse profiles and the micro-structure thus represent reasonably independent signatures at the two extremes of the studied time-scales of the apparent intrinsic variations. The integrated profiles are generally too stable to help probe certain details of the emission mechanism, while the micro-structure appears mostly too variable to clearly distinguish (as yet) between the possible emission mechanisms. The subpulses, by comparison, do show rich variety in their fluctuations that can be studied using moderate time resolutions and spans of single-pulse sequences.

The subpulses, in a broad sense, represent the actual emission entities that define the structure of individual pulses, and carry information "coded" through the variation in their intensity and location in longitude. The fluctuations may be classified as phase and/or amplitude modulations within/of the overall pulse envelope. The phenomenon of "nulling" may be treated as a special form of amplitude modulation, while that of "drifting subpulses" is primarily a case of phase modulation. The subtle interplay between these two continues to be a topic of considerable interest. However, for the present, we will look at the drifting-subpulse phenomenon alone in some detail.

Drifting subpulses

Soon after the initial identification of "drifting subpulses" by Drake & Craft (1968), fluctuation-spectral analysis (taken over from scintillation studies) found its place in assessing pulse sequences for periodicity (Lovelace & Craft 1968), and efforts were made by several groups to study the subpulse modulation in the then known stars (see Deshpande & Rankin 1999, and references therein). Backer (1973) systematized the then existing studies, developed the crucial technique of applying fluctuation-spectral analysis to each narrow longitude interval within the emission window (and following the varying phase of a feature with longitude), and introducing the generalized concept as well as the terms within which the phenomenon is now almost universally understood.

Several pulsars showing amplitude/phase modulations have been studied using the above techniques over the past decades, and the periodicities characterizing them have been estimated (see Rankin 1986, and references therein). The modulations, though appearing in most cases as quasi-periodic, show remarkably stable periodicities in some cases. The modulation periods, denoted by P_3 and measured in units of the spin period P_1, range from 2 to less than 20. There is another periodicity, P_2, that is commonly used to denote the subpulse separations (or the drift-band separations) and is quoted in degrees of rotational longitude. Understandably, this measure P_2 is relevant only in the case of phase modulation (*i.e.,* drifting subpulses). The so-called "Nyquist-limit" which translates to P_3 being always ≥ 2, is a result of sampling (a given longitude) at a rate no faster than once per spin-period. How far the presently estimated P_3 values suffer from the possible aliasing is not at all clear. However, it seems possible to largely overcome this limitation in a simple way as we shall see shortly.

The beautiful sequences of "drifting" subpulses observed in some radio pulsars have been regarded as among the most salient and potentially instructive characteristics of their emission, not least because they have appeared to represent a system of subbeams, in motion within the emission zone of the star. Numerous studies of these "drift" sequences have been published, and a model of their generation and motion articulated long ago by Ruderman & Sutherland (1975); but efforts thus far have failed to establish an illuminating connection between the drift phenomenon and the actual sites of radio emission. If, indeed, a rotating system of subbeams is responsible for the observed "drifting", then the circulation time $\hat{P}_3$ would be much longer than the interval P_3 between the drift bands. Whether or not the ratio $\hat{P}_3/P_3$ should (always) be an integer is unclear.

With this background, we will glance at some of Joanna Rankin's and my collective attempts to address some of the issues mentioned above. For the further discussion, we will concentrate on the case of a well-known drifter B0943+10, that we have studied in detail (Deshpande & Rankin 1999), as an

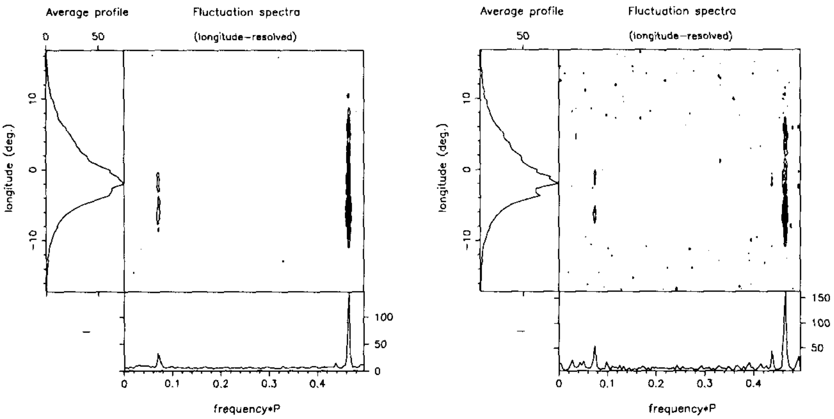

Figure 1. The longitude-resolved fluctuation spectra (center panel) show spectral power as a function of longitude and frequency. The integral spectrum is given in the bottom panel. Note the primary and secondary features at about 0.46 and 0.07 cycles/period as well as the symmetrical "sidebands" around the former. Data (a: for 816 pulses; b: for pulse no. 129-384) on B0943+10 at 430 MHz.

example to illustrate our analysis. As we shall see, our approach is relevant, in general, to other pulsars too.

B0943+10: a case study

The pulsar B0943+10, identified as a conal-single type, was discovered at a low radio-frequency (Vitkevich *et al.* 1969). The shallow polarization PA-sweep and the unusual steepening of its high-frequency spectrum suggest that our sight-line samples its emission cone ever more tangentially with increasing frequency. We begin by applying the longitude-resolved fluctuation spectral technique (Backer 1973), to 0943+10 using the "B"-mode single-pulse sequence (816 pulses) at 430 MHz discussed in Suleymanova *et al.* (1998), and the result is shown in Fig. 1a. The spectrum shows a prominent feature at ~0.46 c/P_1 and a weaker one at 0.07 c/P_1. The high Q (~ 500) associated with the primary feature implies extra-ordinary stability in its drift patterns.

We have resolved the long-standing question of whether this primary fluctuation spectral feature is aliased and whether the secondary feature is its second harmonic. For this purpose, we examine the fluctuation properties of the subpulse sequences in a simple, yet novel manner that overcomes the so-called Nyquist limit (of 0.5 c/P_1) encountered in the conventional longitude-resolved fluctuation-spectral analysis. Our spectral analysis method (of a harmonic-resolved spectrum) exploits the fact that any (phase or amplitude) modulation of (or within) the repetitive envelope of the pulsar signal is sampled also within the finite width of the pulse. This facilitates *complete* unfolding of the otherwise aliased spectra, and hence a direct determination of the modulation periodic-

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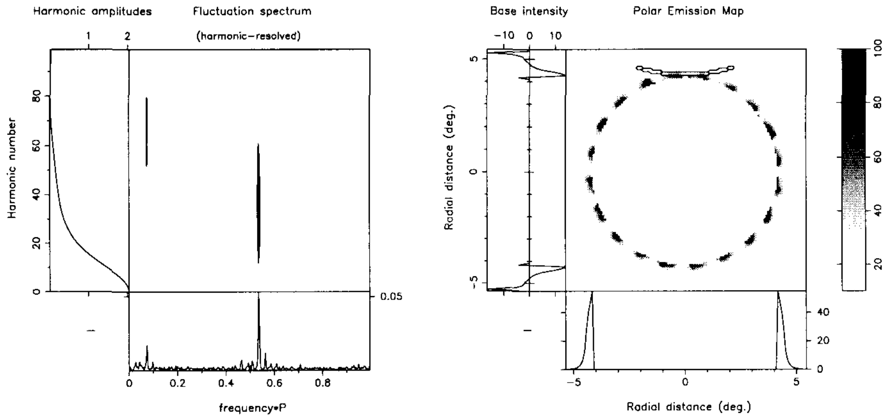

Figure 2. a) A contour plot of the fluctuation spectrum, of a continuously-sampled time sequence reconstructed from the (gated) single-pulse sequence, viewed in a matrix form with each row showing a section of the spectrum between n/P_1 to $(n+1)/P_1$ for harmonics $n = 0, 1, 2, ...$ of the spin frequency $1/P_1$. b) Results of the "cartographic" transformation. The single-pulse sequence has been mapped onto a rotating frame centred on the magnetic axis. A part of the sight-line traverse is shown at the top of the figure.

ity (see Fig. 2a[1]). Although this analysis is applied here to phase-modulated signals, it is equally relevant to amplitude modulation.

Using this new fluctuation spectral analysis, we identify the "true" periodicity ($P_3 \sim 1.87P_1$) in the drift patterns to be a little faster than $2P_1$. We also establish that the two main features in the fluctuation spectrum are definitely harmonically related and estimate accurately the drift-band (or subpulse) separation (P_2 ~10.5^o). Combining this estimate with the polarization information (reflecting the viewing geometry), we make a first-order estimate of the round-trip circulation time —if, indeed, the drift behavior is a result of an emission pattern in rotation around the magnetic axis of the star. Noting that this implied circulation time is much shorter than the time over which drift rates appear to be stable (apparent from the high "Q" of the spectral features), we look for spectral signatures reflecting the *circulation time.* We identify such a signature in form of a pair of "sidebands" around the primary modulation feature (Fig. 1b). The detection of these sidebands not only confirms the "circulation" hypothesis, but allows us to conclusively assert the period (37.4 P_1 or 41 s) and the sense of the circulation as well as of the star-spin. This level of analysis and parameter estimation has simply not been possible earlier for any pulsar. We then confirm

[1]The harmonics at n/P_1 (the Fourier components of the average profile) are shown separately (left panel), and the bottom panel gives the column sum over frequencies viewed as modulo $1/P_1$ (for comparison with Fig. 1a,b). Note that the principal feature now falls at an (unaliased) frequency of about 0.535 c/P_1. Note also that whereas the Fourier amplitudes of the principal feature peak at about harmonic (row) number 35 (corresponding to P_1/P_2), those of the secondary feature peak around number 70—thus demonstrating their harmonicity.

that the circulation time corresponds to a system of 20 emitting entities in rotation along an almost-circular track (with less than 5% deviation). Motion of the emitting entities along tracks that deviate significantly from circular require quite contrived configurations and hence appear unlikely.

Pursuing further this unavoidable (and most likely) hypothesis that a system of subbeams rotate around the magnetic axis of the star, we develop a new technique, a cartographic transform, for mapping the pattern of subbeams that is responsible for the observed single-pulse sequence. The cartographic transform involves only a simple transformation of coordinates, from those defined with respect to the spin axis of the star to that in a rotating frame around the star's magnetic axis. This way of mapping the underlying emission pattern for 0943+10 at 430 MHz shows a B-mode (pulses 1–816) pattern of 20 subbeams, spaced uniformly in azimuth along a ring near the inner-most magnetic colatitude accessible from our sight-line (Fig. 2b).

To check the consistency, of, in general, the results of our mapping technique and, in particular, the parameters that *define* the transform, we introduce an "inverse" cartographic transform that is applied to the *average* map to generate an artificial pulse-sequence for a detailed comparison with the original one. The comparison is quantified by a measure of cross-correlation between the two sequences (pulse-by-pulse and longitude-by-longitude). This comparison is most sensitive to any mismatch in the details of the fluctuations (and the corresponding spectra). It is worth emphasizing here that this *closure* check derives its subtle sensitivity from the fact that (or provided that) the resulting map is an average[2] of contributions from a number of pulses over many circulation times or from many sight-line traverses through the emitting elements. For a motion that is perfectly circular, the averaging (of data from the pulse-sequence) occurs only across the magnetic azimuth and not along the map radius[3]. In the present case, it was possible to provide initial guesses for the parameters defining the cartographic transform with adequate accuracy and then refine them through the closure criterion. This benefited also from our detailed modelling of the viewing geometry, using the polarization PA data as well as the profile widths over a wide range of radio frequencies. Interestingly, we find that the spectral evolution of the size of the emission cone is rather slow.

To summarize, our "cartographic" technique for disentangling the complex single-pulse observations into more comprehensible emission patterns promises to be a powerful tool for assessing and improving our understanding of the physical mechanism of pulsar radio emission. By applying the mapping technique to successive short sections of the observations, it has been possible to examine the

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[2]The situation can be readily appreciated in a very familiar 1-d analogue where an average-pulse profile (shape), obtained by averaging a number of single pulses at an assumed spin period, is compared with the single-pulse profiles, and the comparison is used to check the consistency of the assumed period. It follows that the sensitivity of such a comparison depends directly on the amount of averaging. Also, the quantitative measure (say, a suitably defined cross-correlation coefficient) for such a comparison would show peaks at, in general, even the integral multiples of the *true* spin-period. Thus, while *searching* for the *true* periodicity, it is important to be guided by an initial guess adequately close to the "true" value.

[3]This is the reason why the closure checks are less sensitive to a mere overall scaling in the (angular) size of the map in comparison with other parameters in the cartographic transform.

associated qualitative changes in the polar emission pattern. To see how typical the mapped emission pattern in the B-mode is, we have examined sequences observed in 1972 at 430 MHz as well as a 1990 set at 111 MHz[4]. These results combined with that from a similar mapping at 35 MHz (Asgekar & Deshpande 1999), lead us to the conclusion that we are viewing a rotating system of emission *columns* and that there is a common underlying pattern that dictates the observed fluctuation properties depending on the relative viewing geometries at different frequencies (that are emitted at different heights from the stellar surface). The cartoon that captures the observed behavior in the present case has remarkable overlap with the model articulated by Ruderman & Sutherland (1975) for the drifting-subpulse phenomenon. It is important to stress here that our analysis and the conclusions that follow directly from it do *not* depend on the R&S model. However, they seem to lend considerable support to their suggestion of a circulating pattern being responsible for the subpulse drift. Regardless of whether the model is correct in its detailed emission physics, we believe that the $\mathbf{E}\times\mathbf{B}$ drift invoked in the model is the most likely cause for the circulation. We find that the relevant time-scales in the model are consistent with what we observe in the case of 0943+10. However, it is important to extend the analysis to other pulsars with different parameters and viewing geometries for a more detailed quantitative assessment.

Similar analyses of the Q-mode sequence and polarized components are discussed in Rankin & Deshpande (1999, this volume). A more detailed discussion on the implications of our results is given in Deshpande & Rankin (1999; 2000).

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[4]Moving images can be viewed using netscape at http://www.rri.res.in/~desh and http://www.uvm.edu/~jmrankin

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