Characterising the nature of Subpulse Drifting in Pulsars

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ABSTRACT

We report a detailed study of subpulse drifting in four long period pulsars. These pulsars were observed in the Meterwavelength Single-pulse Polarimetric Emission Survey and the presence of phase modulated subpulse drifting was reported in each case. We have carried out longer duration and more sensitive observations lasting 7000-12000 periods, between frequency range of 306 and 339 MHz. The drifting features were characterised in great detail including the phase variations across the pulse window. In two pulsars J0820$-$1350 and J1720$-$2933 the phases changed steadily across the pulse window. The pulsar J1034$-$3224 has five components. The leading component was very weak and was barely detectable in our observations. The four trailing components showed the presence of subpulse drifting. The phase variations changed in alternate components with a reversal in the sign of the gradient. This phenomenon is known as bi-drifting. The pulsar J1555$-$3134 showed the presence of two distinct peak frequencies of comparable strengths in the fluctuation spectrum. The two peaks did not appear to be harmonically related and were most likely a result of different physical processes. Additionally, the long observations enabled us to explore the temporal variations of the drifting features. The subpulse drifting was largely constant with time but small fluctuations around a mean value was seen.

Key words: pulsars: general - pulsars: individual: J0820$-$1350, J1034$-$3224, J1555$-$3134, J1720$-$2933.

1 INTRODUCTION

The radio emission from pulsars is highly pulsed and usually occupy a small fraction of the pulsar period. The single pulses consist of one or more individual subpulses. In certain pulsars it is seen that the subpulses exhibit a periodic variation within the pulse window either in their location or amplitude or both and the phenomenon is known as subpulse drifting (Drake & Craft 1968).

There are around 120 pulsars where this phenomenon has been reported (Weltevrede et al. 2006, 2007; Basu et al. 2016). The subpulse drifting can be broadly categorised into two distinct classes, the phase modulated drifting, where the subpulses show a steady shift in position across the pulse window, and the amplitude modulated drifting, where the subpulses are stationary within the pulse window but periodically change in intensity. The fluctuation spectral analysis (Backer 1973; Backer et al. 1975), which involve carrying out Fourier transforms for a number of consecutive single pulses along specific pulse longitudes, illustrate the different drifting classes in pulsars. The drifting periodicity is seen as a peak in the fluctuation spectrum. The subpulse motion across the pulse window, on the other hand, is seen as a phase variation corresponding to the peak frequency. The amplitude modulated drifting shows a relatively flat phase behaviour across the pulse window while the phase modulated drifting shows large systematic phase changes.

The radio emission from pulsars is expected to arise due to the growth of instabilities in the relativistic plasma outflowing along the open magnetic field lines (Asseo & Melikidze 1998; Melikidze et al. 2000; Gil et al. 2004; Mitra et al. 2009). The plasma has been proposed to originate from an inner acceleration region (IAR) above the polar cap in the form of sparking discharges (Ruderman & Sutherland 1975). In this scenario the subpulse drifting is related to the plasma dynamics which is governed by the $E \times B$ drift in the IAR. The subpulse drifting is a consequence of the sparks lagging behind corotation of the star. Using this concept a new relationship between the drifting and the spin down energy loss ($\dot{E}$) was established by Basu et al. (2016). The drifting periodicity ($P_3$), for the phase modulated drifting, was found to be anti-correlated with $\dot{E}$, $P_3 \propto \dot{E}^{-0.6} P$, where $P$ is the pulsar period. The amplitude modulated drifting, on the other hand, showed no clear dependence on $\dot{E}$. Additionally, the phase modulated drifting was only seen in pulsars with $\dot{E} < 2 \times 10^{32}$ erg s$^{-1}$. The periodic subpulse modulation seen in pulsars with $\dot{E} > 2 \times 10^{32}$ erg s$^{-1}$ exclusively belonged to the amplitude modulation class. It has been shown by Basu et al. (2017) that the periodicities of amplitude modulation are similar to periodic nulling, implying a common origin for both. It was also suggested that periodic ampli-
tude modulation is a different phenomenon from phase modulated subpulse drifting, hereafter simply subpulse drifting.

As the pulsar rotates the line of sight traverses from the leading to the trailing edge of the pulse window. The phase variations, seen from the leading to the trailing edge of the window, can be broadly categorised into two classes. The first group is called negative drifting and the phases show a positive slope from the leading to the trailing edge. The subpulses in negative drifting are shifted towards leading part of the profile with increasing time. The positive drifting on the other hand corresponds to the case where the phase changes show a negative slope from the leading to the trailing edge of the pulse window. In this case the subpulses shift towards the trailing part of the profile in subsequent periods. The positive and negative drifting originate due to different reasons in competing models explaining this phenomenon. According to the carousel model (Gil & Sendyk 2000; Deshpande & Rankin 2001) the subpulse drifting originates due to the rotation of the sparking discharges in the IAR around the magnetic axis. The drift direction can be attributed to either the clockwise or anti-clockwise rotation of the sparking system. Additionally, depending on whether the line of sight cuts the emission beam inwards or outwards from the rotation axis the drift direction is reversed. In a second model for subpulse drifting, where the sparks in the IAR are expected to lag behind corotation (Basu et al. 2016), the drift direction is representative of the aliasing effect around 2P. The subpulses in subsequent periods have an intrinsic motion from the trailing to the leading edge. If the drift periodicity is more than 2P the positive drifting is seen. The negative drifting occurs if the drift periodicity is less than 2P.

The Meterwavelength Single-pulse Polarimetric Emission Survey (MSPES, Mitra et al. 2016) was carried out to study the radio emission properties of 123 pulsars. Basu et al. (2016) conducted fluctuation spectral studies to characterise the periodic sub-pulse behaviour in these pulsars. They concentrated primarily on the drifting periodicity and did not address phase changes associated with them in detail. One primary reason for this is such studies require very sensitive observations covering a large number of single pulses which are restricted in the survey setup. In this work we have characterised the subpulse drifting in four pulsars observed in MSPES using more sensitive studies. These pulsars were selected based on their prominent drifting features as well as high signal to noise detections of the drifting peaks in the fluctuation spectra. We have carried out long observations of these sources and carried out the most sensitive phase variation studies for their drifting features. In addition, we have also investigated the temporal variations of the subpulse drifting phenomenon using the long observations.

2 OBSERVATIONS AND ANALYSIS

We have observed the four pulsars in Table 1 using the Giant Meterwave Radio Telescope (GMRT), which is located near Pune, India (Swarup et al. 1991). The GMRT is an interferometric array consisting of thirty antennas each of forty five meters diameter, with fourteen antennas located within a central square kilometer area and the remaining sixteen antennas spread along three arms in a Y-shaped array. We have used the Telescope in the phased array mode where the signals from different antennas were co-added. In order to reach sufficient sensitivity for single pulse studies we used approximately twenty antennas, including all the available central square antennas and the two nearest arm antennas. A phase calibrator was recorded at the start of each observation and subsequently after every hour. Appropriate “phasing” solutions were estimated to correct for temporal gain variations in each antenna. The pulsars were observed on November 4 and 5, 2015 with each pulsar recorded for durations between 7000 and 12000 periods. In some cases there were phasing breaks in between the observations of a source.

Total intensity signals were recorded at frequencies between 306 and 339 MHz, covering a bandwidth of 33 MHz and spread out over 256 frequency channels. This resulted in higher sensitivity detection of single pulses compared to MSPES, where the signals were recorded in the full polarization mode but over 16 MHz bandwidth. The time resolution for these observations was 491.52 microseconds. The dispersion spreads across the frequency band were corrected using the known dispersion measures of the pulsars and the signal was subsequently averaged along the frequency band to produce a time series corresponding to the radio emission from each pulsar. In order to maintain continuity in the overall time series data during phasing breaks suitably weighted noise signals were inserted during these intervals. Finally, the time series signals were re-sampled to form a two dimensional pulse stack with one axis along the pulse longitude, separated into integral bins, and the other along the pulse number (see figure 1). Further information about the initial analysis is detailed in Basu et al. (2016, see appendix A).

We have used the fluctuation spectral analysis to explore the subpulse drifting in the four pulsars studied in this work (Backer 1973; Backer et al. 1975). The primary analysis scheme was the Longitude Resolved Fluctuation spectra (LRFS) where Fourier transforms across each longitude, for 256 consecutive single pulses, were carried out. Subsequently, the starting point was shifted by fifty periods and the process was repeated till the end of the observations. Each LRFS realisation had two constituents, the amplitude with one or more peak frequencies (f_p in units of cycles/P), and the corresponding phase at f_p giving the nature of subpulse variation across the pulse window. In Basu et al. (2016) we proposed a method to quantify the temporal variation in LRFS amplitude by stacking the average across the pulse window as a function of the starting period. Two consecutive spectra separated in this work were separated by ten periods¹). In order to reduce the effect of the unknown baseline level the time average peak intensity in the LRFS was normalized to unity. The primary drawback of this method was that the information across the the pulse window was lost due to averaging. Also, no information was preserved regarding the phase variations. Additionally, it was seen that the gaps in the data during telescope phasing resulted in strong low frequency peaks which suppressed the drifting peaks in the average spectra. In order to mask these unwanted peaks we estimated the baseline rms level of the LRFS and replaced the affected LRFS intervals during phasing with simulated noise.

In this work we have devised another method to study the nature of subpulse drifting using the fluctuation spectra. Similar, to the previous case the individual FFTs for 256 consecutive periods were estimated for the entire observing run by shifting the starting point by fifty periods. The first step was to estimate the peak amplitude of the fluctuation spectra as a function of the pulse longitude. The f_p from the average LRFS and the corresponding error, δf_p, ¹ we have replaced ten periods by fifty periods in this work. We found this did not affect the estimation of temporal variation of the signal, since, this was well below the FFT lengths, but this considerably saved computation time.
Figure 1. The figure shows a section of the single pulse stacks comprising of 256 consecutive periods for the four pulsars J0820−1350, J1034−3224, J1555−3134 and J1720−2933.

Table 1. Observing Details.

| Pulsar       | Period (sec) | DM (pc cm\(^{-3}\)) | \(\dot{E}\) (10\(^{31}\)erg s\(^{-1}\)) | Npulse |
|--------------|--------------|-----------------------|------------------------------------------|--------|
| J0820−1350   | 1.238        | 40.94                 | 4.38                                     | 10199  |
| J1034−3224   | 1.150        | 50.75                 | 0.597                                    | 7837   |
| J1555−3134   | 0.518        | 73.05                 | 1.77                                     | 6947   |
| J1720−2933   | 0.620        | 42.64                 | 12.3                                     | 11660  |

was determined. Here \(\delta f = \text{FWHM}/2.355\), FWHM being the Full Width at Half Maximum of the peak (Basu et al. 2016). Now, for each 256 period FFT we looked for the maximum value within the error window at each longitude (i.e \(f_p - 3\delta f < f < f_p + 3\delta f\)) and any significant measurement (\(>3\) times the rms level of the baseline) was identified. In addition the \(f_p\)s at each longitude, for all the different measurements of the LRFS, were averaged and the value was overlayed on top of the individual measurements. This is shown in Figure 2 (right plot, top panel), where the small red dots represent the maximum amplitude corresponding to \(f_p\) for all LRFS realization and the black dots show the average value. The phase variations, corresponding to the peak amplitude, were also estimated similarly (see Figure 2, right plot, middle panel). However, one additional step was followed while estimating the phase variations. The fifty period shift between two consecutive LRFS was not an integral multiple of the drifting periodicity (\(P_3\)) and resulted in arbitrary phase differences between different realizations of the LRFS. This would result in smearing of the peak phase information in the average behaviour. To address this issue we have a priori fixed the phase at a certain pulse longitude, the profile peak intensity, to be zero and estimated the variation of the phases across the window. The absolute phase information during each LRFS is lost but the information regarding the relative phase variation across the pulse window is not washed away. For both the estimates of the peak amplitude and phase at any longitude we have only considered significant measurements, i.e. the measured frequency peak was greater than 3\(\sigma\) level of the baseline.

The above method of estimating the variation of drift phase is a superior technique for pulsars with long uninterrupted drifting patterns. This is primarily because some of the phase information at certain longitudes which were lost during any specific LRFS realization due to weaker signal strengths can be recovered during the longer integrations. Earlier techniques (eg. van Leeuwen et al. 2002) have used prominent single pulse sequences to establish the nature of subpulse motion within the pulse window. In these cases the results were likely to be biased by that particular sequence of single pulses. The sensitivity of estimating the subpulse motion would also be affected by the errors in localising the subpulse peaks. We have also determined the average pulsar profile within the pulse window as shown in right plot, bottom panel of figure 2. We did not have absolute flux calibration for the profiles and normalized the profile peak to unity in these plots.

3 THE SUBPULSE DRIFTING IN INDIVIDUAL PULSARS

We have applied the analysis schemes described in the previous section to study in detail the temporal as well as longitudinal vari-
ation of subpulse drifting in all four pulsars. We have employed two main analysis techniques for these studies. The first technique involved averaging the LRFS across the pulse window and estimating its temporal variation. The second technique involved finding the peak amplitude and look for its variation, as well as the phase associated with it, as a function of longitude. All the time realizations in the second exercise were seen as a spread around a mean value at each longitude.

3.1 J0820–1350

In figure 2, left plot, the temporal variation of the average LRFS is shown. The peak frequency is $f_p = 0.211 \pm 0.009$ cycles/$P$ and the Full Width Half Maximum (FWHM) of the peak is 0.021 cycles/$P$. This corresponds to drifting periodicity $P_3 = 4.7 \pm 0.2$ $P$. In order to estimate the relative strength and spread of the drifting feature an $S$ factor was introduced by Basu et al. (2016). This was defined as $S = \sigma_v / \text{FWHM}$, where $\sigma_v$ is the separation between the frequency peak and the baseline level of the fluctuation spectra. The time averaged LRFS peak for this measurement had $S = 38.9$. The above results for peak in the LRFS and the corresponding drifting periodicity is compatible with the measurements reported in Basu et al. (2016). The frequency peak despite its relatively high $S$ value is not sharply defined either in the individual LRFS or in their time evolution. The spread of the peak frequency in the LRFS has interesting implications about the physical conditions in the IAR which we discuss in the next section. The right plot in figure 2 presents the change of drifting features across the pulse window. The top part shows the variation of the peak intensity while the middle part shows the variation of the phase associated with the peak. The pulse window, defined at $5\sigma$ above baseline level, is between -8.5$^\circ$ and +10$^\circ$ longitude with the peak intensity at 0$^\circ$. A dip in the LRFS peak amplitude is seen around +1$^\circ$ from the intensity peak while the corresponding peaks on either side were at -0.5$^\circ$ and +3.0$^\circ$. The peak phases (middle panel, right plot) show a large variation (> 600$^\circ$) across the pulse window. The phases across the pulse window do not vary in a linear manner. The phase variations are flatter in the leading part of the profile which becomes more steep around the peak pulse and then once again relatively flat near the trailing edge.

The pulsar J0820–1350 is a well known example of nulling and drifting appearing in the same system. The subpulse drifting was first measured by Lyne & Ashworth (1983) who reported a change in the drift rate before and after the onset of nulling. We have detected short duration nulls lasting between 1-2 periods. No periodicity was detected associated with the occurrence of these short nulls (Basu et al. 2017). The change in drifting behaviour around the onset of nulls has been reported in other pulsars like B0031–07 (Vivekanand & Joshi 1997; Smits et al. 2005; McSweeney et al. 2017) and B0809+74 (Lyne & Ashworth 1983; van Leeuwen et al. 2002). However, the state changes are more distinct in these pulsars and nulling lasts for longer durations which makes such identification more easier. In fluctuation spectral analysis any deviation in subpulse tracks would show up as deviations in the phase behaviours. As seen in the phase variations for the entire observing run the phases are bunched up together indicating no large jumps or variations around the onset of short nulls. However, we cannot rule out small phase variations around nulls which can be hidden within the spread of the phase measurements. The median value of the spread in the phase bunches across all longitudes is 11.9$^\circ$$\pm$2.4$^\circ$. A detailed study of the subpulse variation across the pulse window was carried out by Biggs et al. (1987). Their estimates of the variation of the amplitude of the peak frequency across the pulse window is consistent with our results. They estimated the phase difference between two longitude bins and showed the phase track to be steeper near the center of the profile and relatively flatter near the edges. This is consistent with our measurements. The subpulse drifting in this pulsar has also been studied by Weltevrede et al. (2006, 2007) at two frequencies, 325 and 1360 MHz. They used the two dimensional fluctuation spectrum (2DFS, Edwards & Stappers 2003) and reported horizontal structures which is indicative of non-linear drift bands at both wavelengths. The relative steepening of the phase variations towards the center of the profile was also seen in their work with the effect being more pronounced at the higher frequency. Janssen & van Leeuwen (2004) using the carousel model suggested that the drifting slows down during the null state and the subpulse drift in this pulsar was aliased. The pulsar has also been detected in intermittent and longer null states in the past. Despite our relatively long observations the emission was in the bright state throughout. However, the 333 MHz observations in MSPES found the pulsar in the low intensity/null states. The pulsar in this state showed the presence of drifting with exactly the same properties as the bright state.

3.2 J1034–3224

The pulsar with five components has a relatively wide profile with the $5\sigma$ boundaries lying between -45$^\circ$ and +61$^\circ$, where the peak intensity is centered around zero longitude. The leading component is very weak and appears sporadically with the peak located around -28$^\circ$ and is similar to pre-cursor emission (Basu et al. 2015). The subpulse drifting in this pulsar was reported for the first time by Basu et al. (2016). No drifting feature could be detected for the leading component. The remaining four components all showed subpulse drifting with the same periodicity as shown in figure 3. The left plot of the figure shows the temporal variation of the LRFS where the peak frequency is $f_p = 0.139 \pm 0.014$ cycles/$P$. This corresponds to a drift periodicity of $P_3 = 7.2 \pm 0.7$. The FWHM of the peak is 0.033 cycles/$P$ which puts the strength of the peak value to be $S = 12.6$. These measurements of the drifting properties are consistent with previous values. The temporal variations of the LRFS shows that the peak frequency has a certain width around the peak value which has interesting implications for the IAR. Additionally, the time average LRFS shows the presence of a wider structure in the fluctuation spectra peaking at zero frequency and sitting underneath the subpulse drifting peak. The origin of this wider structure in the fluctuation spectra was not clear. There are presence of horizontal stripes seen in the time variation of the LRFS. These stripes are indicative of the alteration in the baseline level of the fluctuation spectra with time. The baseline level corresponds to the mean value of the signal and would be zero if the mean value is zero. In our case the existence of horizontal stripes imply that the mean profile value over 256 periods is not constant but changes with time. If we had a continuous shift in the starting period rather than a 50 period shift the variations would be continuous and not appear as stripes. The stripes are most visible in this pulsar due to its relatively weaker peak amplitude which makes the baseline variation more clearly visible.

The right plot in figure 3 shows the variation of the peak amplitude (top panel) as well as the phases associated with them (middle panel) as a function of the pulse longitude. The amplitude of the peak frequency is maximal for the second component which is also the strongest in the profile. The third and fifth components are relatively weaker with roughly one fourth of the second com-
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Figure 2. The figure shows the temporal variation of the LRFS in the pulsar J0820−1350. Each LRFS was determined for 256 consecutive periods and the temporal variations were estimated by shifting the starting period by fifty pulses. The left plot shows the average LRFS across the whole pulse window as a function of the starting period. The two regions in between with no signal correspond to breaks in the observations during phasing of antennas which have been masked with simulated noise. The right panel represents the variation of the LRFS across the pulse window for different time realizations for the peak amplitude (top panel), the corresponding phase variations (middle panel) and the average profile (bottom panel). The temporal variations are seen as a spread of the amplitudes as well as the phases while the average value at each longitude is shown as a black dot. The profile peak was the reference point for aligning the phases in each LRFS.

ponent while the fourth component has weakest drifting with about one tenth the peak value despite it being of comparable strength in the profile with the third and fifth component. The phase variation on the other hand shows the rarest and fascinating phenomenon of bi-drifting (Qiao et al. 2004b). The phase variations in the second and fourth components have positive slope while the third and fifth components have negative slope, indicating drift reversals between adjacent components. The improved phase estimation technique in this work have made the identification of bi-drifting possible in this pulsar which was earlier proclaimed to have a complex phase behaviour (Basu et al. 2016). The analysis technique loses the absolute phase information of the peak frequency, however the relative phase information across the profile is preserved. We have measured the phase variations in different parts of the profile which apart from the reversals are more or less linear. The absolute phase relationship between the leading and trailing part of the profile could not be measured due to the gap in between. Thus a possible phase shift of 360° may be present between these two parts of the pulse window. The phase roughly increases from -16° to +12° in the longitude range -4° to +3° corresponding to the second component. The third component is wider and spread between the longitude range +3° to +20°. The phase in this region roughly decreases from +12° to -150°. The drifting in the fourth component with the weakest features is confined between longitude range +35° and +39° and the phase increases from +70° to +200°. Finally, the fifth component has drifting features extending from +42° to +52° in longitude with the phase decreasing from +150° to +80°.

As mentioned earlier, the bi-drifting phenomenon is extremely rare and reported in two other pulsars, J0815+0939 (Champion et al. 2005; Szary & van Leeuwen 2017) and B1839−04 (Weltevrede 2016). In case of PSR J0815+0939 the pulsar exhibit four components with the opposite phase variation seen only in the second component. In case of B1839−04 there are two components whose phases show opposite slopes. In this regard PSR J1034−3224 is unique since it shows multiple drift reversals with alternate components having opposite direction of phase variations. The bi-drifting phenomenon is extremely difficult...
Figure 3. The figure shows the temporal variation of the LRFS in the pulsar J1034−3224. Each LRFS was determined for 256 consecutive periods and the temporal variations were estimated by shifting the starting period by fifty pulses. The left plot represents the average LRFS across the whole pulse window as a function of the starting period. The region in between with no signal corresponds to breaks in the observations during phasing of antennas which have been masked with simulated noise. The right plot shows another realization of the LRFS by showing the variations across the pulse window of the peak amplitudes for all times (top panel), the corresponding phase variations (middle panel) along with the average profile (bottom panel). The temporal variations are seen as a spread of the amplitudes as well as the phases while the average value at each longitude is shown as a black dot. The profile peak was the reference point for aligning the phases in each LRFS.

3.3 J1555−3134

The pulsar shows a classical conal double profile with both components showing the presence of subpulse drifting (Basu et al. 2016). The components are of comparable intensity with the trailing component associated with the profile peak. The $5\sigma$ boundaries of the pulse window are between longitudes $-24^\circ$ and $+11.5^\circ$ where the profile peak is aligned along $0^\circ$. The time varying LRFS of the pulsar is shown in figure 4, left plot, where both components have similar drifting periodicities. The pulsar shows the presence of two distinct peaks in the fluctuation spectra with $f_{p,1} = 0.057\pm0.012$ cycles/$P$ and $f_{p,2} = 0.098\pm0.010$ cycles/$P$. Though the errors are large the peaks do not appear to be harmonically related. The corresponding strengths of the peaks are $S_1 = 20.6$ and $S_2 = 22.2$ which shows that they are of similar strengths. The FWHM of the peaks are 0.027 cycles/$P$ and 0.025 cycles/$P$ respectively and the peaks show some spread in single realizations of LRFS as well as in their time evolution. The drifting periodicities are estimated to be $P_{b,1} = 17.5\pm3.6$ $P$ and $P_{b,2} = 10.2\pm1.0$ $P$ for the two peaks which is consistent with previous measurements.

In figure 4, right plot, the variations of the peak amplitude (top panel) as well as the associated phase (middle panel) are shown as a function of pulse longitude separately for the two different peaks. The peak amplitudes of the two drifting features are not coincident with their maximum being slightly displaced along the x-axis (pulse longitude). As a first step we estimated the phase variations of the two frequency peaks without introducing any arbitrary phase shifts across the pulse window. We estimated multiple iterations of the 256-period LRFS which will have random phase shifts between them. This enabled us to test if the two frequency peaks are harmonically related. If we assume that the phase variations are linear then the first harmonic will show a phase variation with a gradient which is twice that of the fundamental frequency. Thus for different iterations of the LRFS the phase at any longitude corresponding to two harmonics will have a definite relationship. However, the phases to understand from simple models of the IAR which we briefly discuss in the next section.
Figure 4. The figure shows the temporal variation of the LRFS in the pulsar J1555–3134. Each LRFS was determined for 256 consecutive periods and the temporal variation was estimated by shifting the starting period by fifty pulses. The left plot represents the average LRFS across the whole pulse window as a function of the starting period. The fluctuation spectra shows the presence of two distinct frequency peaks. The right plot shows the variation of the LRFS across the pulse window for all times for the peak amplitudes (top panel), the corresponding phase variations (middle panel) along with the average profile (bottom panel). The temporal variations are seen as a spread of the amplitudes as well as the phases while the average value at each longitude is shown as a black dot. The profile peak is the reference point for aligning the phases in each LRFS. The phase variations for the two peaks are shown separately and exhibit a difference across the pulse window.

The estimates of the slopes for the different components and frequency peaks. The phase tracks corresponding to each 256-period LRFS have been approximated with linear fits. We report the mean and rms (error) of the distribution of the slopes for the observing durations.

|                  | leading Comp. | Trailing Comp. |
|------------------|---------------|----------------|
| Peak 1           | 22.1±7.6      | 18.5±3.7       |
| Peak 2           | 20.3±4.7      | 21.1±2.6       |

There is a possibility that the two peaks are not actually simultaneous but the pulsar switches very rapidly between the two drift-
ing states at timescales less than 256 periods. To test this we used 128 period and 64 period FFT lengths for the LRFS studies. The two peaks were also seen in these measurements indicating their near simultaneity. Any shorter duration studies were not possible since the two peaks merged together and could not be resolved. There have been earlier observations of systems which undergo mode changing with associated change in subpulse drifting periodicity. However, to the best of our knowledge PSR J1555−3134 is currently the only known example where two different drifting periodicities, which are not harmonically related, exist simultaneously. It is also possible that the pulsar switches between these two drifting states at very short timescales. This raises many questions about the conditions in the IAR that can accommodate multiple drift periodicities either existing simultaneously or switching between them at short intervals.

3.4 J1720−2933

The pulsar J1720−2933 is another example where the subpulses seem to move across the entire pulse window, similar to PSR J0820−1350. The pulsed emission is roughly spread between longitude range −12° and +18°. The time variation of the LRFS is shown in figure 5, left plot. Unlike the previous cases the drifting feature in the LRFS is much narrower in individual realizations and shows a jitter with time resulting in a wider average width. To explore the actual width of the drifting feature we have carried out higher resolution analysis. This involved using increasing lengths of pulse sequences to estimate the fluctuation spectra. It was seen that the width stabilized between FFT lengths of 1024 and 2048 periods. We have shown the LRFS measurements in the figure corresponding to 1024 consecutive periods and increasing the starting point by fifty periods. The peak frequency in the time average LRFS is given as $f_p = 0.408 \pm 0.001 \text{ cycles/P}$. The FWHM of the peak frequency is 0.003 cycles/P and the corresponding $S = 337.6$, which is the highest in our list. However, the FWHM is still a factor of two to three larger than in certain individual realizations of the LRFS. The drifting periodicity of the pulsar is $P_3 = 2.452 \pm 0.006 \text{ P}$ which is consistent with the measurements of Basu et al. (2016).

In figure 5, right plot, the change in the amplitude of the frequency peak, as well as the associated phase, with the pulse longitude are shown. The amplitudes show the widest spread across the mean for this pulsar. This is most likely because the single pulses have the weakest signal to noise. In this context the high ordering of the drifting is remarkable and is seen despite the comparative weakness of the pulsar signal. The phases show a large variations increasing steadily from around −50° to about +500° towards the trailing edge. The phase changes are not of linear nature but show a relative flattening towards the trailing edge. However, the variations are from PSR J0820−1350 where the phases show more flattening towards both the leading and trailing edge.

4 DISCUSSION

The most prominent model of subpulse drifting has been proposed by Ruderman & Sutherland (1975) who considered an aligned rotator. The sparking discharges in the IAR lagged behind co-rotation since the plasma density is less than the co-rotation density resulting in the drifting pattern. Alternatively, there are other existing models of non-aligned and non-corotating magnetospheres where the subpulse drifting phenomenon can also to be explored (Melrose & Yuen 2013; Yuen et al. 2016). The validity of the rotating subbeams around the magnetic axis in the form of 'carousel' model in non-aligned rotators was assumed by Gil & Sendyk (2000); Deshpande & Rankin (2001) and subsequent analysis of subpulse drifting was based on this model. The different phase behaviours seen in the population are associated with different line of sight cuts of the emission beam. In recent works it has been suggested that the carousel model is physically inconsistent with the pulsar electrodynamics (Basu et al. 2016; Mitra & Rankin 2017).

In non-aligned pulsars the lagging behind co-rotation imply that the sparks should be moving around the rotation axis and not the magnetic axis as postulated in the carousel model. In addition many models (Gil et al. 2003) require the presence of highly non-dipolar fields in the IAR. The radius of curvature of the field lines in the IAR should be much higher than the dipolar case for the primary plasma to reach sufficient energies for radio emission (see Mitra 2017, for a review of the conditions in the IAR leading to radio emission in pulsars). The presence of non-dipolar fields in the IAR would considerably distort the magnetic field lines in the gap and likely displace the polar cap from its dipolar location. Models for such fields exist in the literature (Gil et al. 2002) where the non-dipolar field have been approximated as a star centered dipole coupled with dipoles, with much smaller dipole moments, on the stellar crust near the IAR. One direct consequence of these conditions is that the spark trajectories in the IAR will be distorted. The phase variations associated with subpulse drifting as shown in our measurements deviate from linear variations across the pulse window. This is likely another indication of the presence of non-dipolar magnetic fields in the IAR. However, no such study exist in the literature where subpulses lagging behind corotation and moving in non-dipolar magnetic fields have been simulated to show the nonlinear phase variations. In certain cases the deviations of the phase variations from linear trend can be explained via line of sight curvature (Edwards & Stappers 2003).

Another aspect of subpulse drifting that has been particularly challenging to understand is the effect of bi-drifting seen in only three pulsars, including J1034−3224. The reversal of phase changes in adjacent profile components cannot be explained either from a simple carousel rotation of subpulses around the magnetic axis as well as the sparks lagging behind corotation around the rotation axis. To understand this effect several exotic models for emission has been suggested. Qiao et al. (2004a) proposed the presence of an Inner Annular Gap in addition to the IAR. In the two gaps the drifting is assumed to be different which accounts for the bi-drifting phenomenon. In recent works it has been suggested that the polar cap associated with the IAR is highly distorted and is elliptical in nature and located further way from the dipolar polar cap. In such cases the bi-drifting effect has been reproduced using the carousel model and the associated line of sight traversing a complex path through the IAR (Sazary & van Leeuwen 2017; Wright & Weltevrede 2017). It should be noted that in all three pulsars where bi-drifting have been observed the profiles are very wide encompassing more than 100° in longitude. This is indicative of the pulsar geometry where the angle between the rotation and magnetic axis should be small. Another promising model for the bi-drifting which has not been explored yet is the lagging behind corotation in the presence of highly non-dipolar magnetic fields in the IAR.

Finally, our studies also show that in the majority of cases the drifting feature is not seen as a narrow peak but shows certain width which further evolves with time. It is possible that the $P_3$ is not sharply defined but jitters around a mean value. It should
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Figure 5. The left plot of figure shows the temporal variation of the LRFS in the pulsar J1720−2933. The pulsar shows one of the narrowest features in the fluctuation spectra. We have used the a higher resolution studies with FFT lengths of 1024 periods to estimate the width of the feature. The temporal variation was estimated by shifting the starting period by fifty periods. The region in between with no signal corresponds to break in the observations during phasing of antennas. The right plot shows the variations of the LRFS across the pulse window for all times for the peak amplitude (top panel), the corresponding phase variations (middle panel) along with the average profile (bottom panel). To obtain higher sensitivity measurements, particularly for the phase, we have used 256 periods to estimate the LRFS for these studies similar to other pulsars. The temporal variations are seen as a spread of the amplitude as well as the phase while the average value at each longitude is shown as a black dot. The profile peak was the reference point for aligning the phases in each LRFS.

It be noted that the subpulses are themselves averaged over thousands of sparks. The origin of any variation on this average effect is not clear to us and requires more detailed modelling of the physical conditions in the IAR. In this scenario the sharp peak associated with the pulsar J1720−2933 is remarkable since it shows highly ordered states. However, even in this pulsar we have shown the peak to jitter around the mean value in longer duration observations. The truly baffling observation for us remains the two frequency peaks seen in the pulsar J1555−3134 which our analysis show are not harmonically related. If we relate \( P_3 \) to the sparking process in the IAR then \( P_3 = d/v_d \), where \( d \) is the average separation between two consecutive sparks and \( v_d \) the drift velocity of the spark. In the IAR \( v_d \) can be further expressed as \( v_d = (\Delta E/B)c \), where \( \Delta E \) is the change in the electric field in the gap during the sparking process, \( B \) the magnetic field in the IAR and \( c \) the speed of light. The variables in the above expression are \( d \) and \( \Delta E \). The average separation between sparks is governed primarily by the mean free path of \( \gamma \)-ray photons in the IAR (Ruderman & Sutherland 1975). In a separate work van Leeuwen & Timokhin (2012) has suggested the drift velocity to depend on the variation of the accelerating potential across the polar cap. However, there are no provisions in the above models to explain the jittering around the mean frequency with timescales spanning several hundred periods. Most of these models deal with steady state configuration with only spatial variations across the IAR. Such requirements for the time variations in the IAR has also been noted by Basu et al. (2017); Mitra & Rankin (2017), in order to explain different phenomenon like periodic nulling or mode changing in certain pulsars. It was suggested in these works that the pair production process in the IAR is periodically or quasi-periodically affected by external triggering mechanism at timescales ranging from minutes to hours. This can also be relevant for the jittering seen in the subpulse drifting peaks. There are also no provisions to accommodate multiple realizations of either \( d \) or \( \Delta E \) to coexist simultaneously or switch continuously between two states at short intervals. The presence of two frequency peaks would require new understanding of the physical processes in the pulsar magnetosphere. Alternative models for drifting subpulses like the ones involving surface oscillations can
be explored to investigate the multiple simultaneous peaks in the fluctuation spectra (Rosen & Clemens 2008).

5 SUMMARY

In this work we have carried out detailed measurements of drifting properties in four long period pulsars which show very different behaviours. In three pulsars J0820$-$1350, J1555$-$3134 and J1720$-$2933 the phase variations are monotonically increasing from leading to the trailing edge, however these variations are not linear. On the other hand the pulsar J1034$-$3224 show the rare phenomenon of bi-drifting with reversals in the direction of phase variation in every alternate profile component. The pulsar J1555$-$3134 show the presence of two different drifting frequencies at the same time which are not harmonically related. The pulsar J1034$-$3224 show the presence of two different drifting frequencies at the same time which are not harmonically related. The peak frequency associated with drifting usually show a jitter around a mean value. This is also true for the most ordered drift pattern in PSR J1720$-$2933 which shows small scale variations in peak frequency with time. The diversity of subpulse drifting reported here is particularly challenging for the different models predicting the physical conditions in the pulsar magnetosphere. The temporal fluctuations of the drifting frequencies, the shape of the phase variations and the presence of the two peaks in the pulsar J1555$-$3134 point towards unexplored physical processes that affect the emission mechanism. The physical processes responsible for the plasma generation take place at timescales of hundreds of nanoseconds to several tens of microseconds (Ruderman & Sutherland 1975). Despite the temporal fluctuations of the peak frequency from the mean value the subpulse drifting exist in an underlying steady state throughout these long observing runs. This demonstrates the pulsar magnetosphere to exist in a steady emission state over long timescales.

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REFERENCES

Asseo, E.; Melikidze, G.I. 1998, MNRAS, 301, 59
Backer, D.C. 1973, ApJ, 182, 245
Backer, D.C.; Rankin, J.M.; Campbell, D.B. 1975, ApJ, 197, 481
Basu, R.; Mitra, D.; Rankin, J.M. 2015, ApJ, 798, 105
Basu, R.; Mitra, D.; Melikidze, G.I.; Maciesiak, K.; Skrzypczak, A.; Szary, A. 2016, ApJ, 833, 29
Basu, R.; Mitra, D.; Melikidze, G.I. 2017, ApJ, 846, 109
Biggs, J.D.; McCulloch, P.M.; Hamilton, P.A.; Manchester, R.N. 1987, MNRAS, 228, 119
Champion, D.J.; Lorimer, D.R.; McLaughlin, M.A.; Xilouris, K.M.; Arzoumanian, Z.; Freire, P.C.C.; Lommen, A.N.; Cordes, J.M.; Camilo, F. 2005, MNRAS, 363, 929
Deshpande, A.A.; Rankin, J.M. 2001, MNRAS, 322, 438
Drake, F.D.; Craft, H.D. 1968, Nature, 220, 231
Edwards, R.T.; Stappers, B.W. 2002, A&A, 445, 243
Weltevrede, P.; Edwards, R.T.; Stappers, B.W. 2007, A&A, 469, 607
Wright, G.; Weltevrede, P. 2017, MNRAS, 464, 2597
Yuen, R.; Melrose, D.B.; Samsuddin, M.A.; Tu, Z.Y.; Han, X.H. 2016, MNRAS, 459, 603
Gil, J.; Melikidze, G.I.; Geppert, U. 2003, A&A, 407, 315
Gil, J.; Lyubarsky, Y.; Melikidze, G.I. 2004, ApJ, 600, 872
Huguenin, G.R.; Taylor, J.H.; Troland, T.H. 1970, ApJ, 162, 727
Janssen, G.H.; van Leeuwen, J. 2004, A&A, 425, 255
Lyne, A.G.; Ashworth, M. 1983, MNRAS, 204, 519
McSweeney, S.J.; Bhat, N.D.R.; Tremblay, S.E.; Deshpande, A.A.; Ord, S.M. 2017, ApJ, 836, 224
Melikidze, G.I.; Gil, J.A.; Pataraya, A.D. 2000, ApJ, 544, 1081
Melrose, D.B.; Yuen, R. 2013, MNRAS, 437, 262
Mitra, D.; Gil, J.; Melikidze, G. 2009, ApJL, 696, L141
Mitra, D.; Basu, R.; Maciesiak, K.; Skrzypczak, A.; Melikidze, G.I.; Szary, A.; Krzeszowski, K. 2016, ApJ, 833, 28
Mitra, D.; Rankin J.M. 2017, MNRAS, 468, 4601
Mitra, D. 2017, JApA, 38, 52
Qiao, G.J., Lee, K.J., Wang, H.G., Xu, R.X., Han, J.L. 2004a, ApJ, 606, L49
Qiao, G.J., Lee, K.J., Zhang, B., Xu, R.X., Wang, H.G. 2004b, ApJ, 616, L127
Ruderman, M.A.; Sutherland, P.G. 1975, ApJ, 196, 51
Rosen, R.; Clemens, J.C. 2008, ApJ, 680, 671
Smits, J.M.; Mitra, D.; Stappers, B.W. 2005, A&A, 440, 683
Swarup, G., Ananthakrishnan, S., Kapahi, V. K., et al. 1991, CuSc, 60, 95
Szary, A.; van Leeuwen, J. 2017, ApJ, 845, 95
van Leeuwen, A.G.J.; Kouwenhoven, M.L.A.; Ramachandran, R.; Rankin, J.M.; Stappers, B.W. 2002, A&A, 387, 169
van Leeuwen, A.G.J.; Timokhin, A. 2012, ApJ, 752, 155
Vivekanand, M.; Joshi, B. C. 1997, ApJ, 477, 431
Weltevrede, P.; Edwards, R.T.; Stappers, B.W. 2006, A&A, 445, 243
Weltevrede, P.; Edwards, R.T.; Stappers, B.W. 2007, A&A, 469, 607
Weltevrede, P. 2016, A&A, 590, 109
Wright, G.; Weltevrede, P. 2017, MNRAS, 464, 2597
Yuen, R.; Melrose, D.B.; Samsuddin, M.A.; Tu, Z.Y.; Han, X.H. 2016, MNRAS, 459, 603
