Low-frequency Observations of the Subpulse Drifter PSR J0034—0721 with the Murchison Widefield Array

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Abstract

The phenomenon of subpulse drifting may hold the key to understanding the pulsar emission mechanism. Here, we report on new observations of PSR J0034—0721 (B0931—07) carried out with the Murchison Widefield Array at 185 MHz. We observe three distinct drift modes whose “vertical” drift band separations ($P_3$) and relative abundances are consistent with previous studies at similar and higher frequencies. The drift bands, however, are observed to change their slopes over the course of individual drift modes, which can be interpreted as a continuously changing drift rate. The implied acceleration of the intrinsic carousel rotation cannot easily be explained by plasma models based on $E \times B$ drift. Furthermore, we find that methods of classifying the drift modes by means of $P_3$ measurements can sometimes produce erroneous identifications in the presence of a changing drift rate. The “horizontal” separation between drift bands ($P_3$) is found to be larger at later rotation phases within the pulse window, which is inconsistent with the established effects of retardation, aberration, and the motion of the visible point. Longer observations spanning at least ~10,000 pulses are required to determine how the carousel rotation parameters change from one drift sequence to the next.

Key words: pulsars: general – pulsars: individual (J0034—0721)

1. Introduction

Despite nearly half a century of observational and theoretical investigations, the physical mechanisms responsible for the radio emission from pulsars remain unresolved (Michel 1991; Gurevich et al. 2006; Melrose & Yuen 2016). Some features of observed pulsar emission are considered vitally important to furthering our understanding of these fundamental processes. Chief among these is the phenomenon of subpulse drifting, which is the systematic shift in pulse phase of substructures within individual pulses over time (Drake & Craft 1968). Also critical is nulling, in which the radio emission appears to switch off temporarily (Backer 1970; Ritchings 1976), a widespread phenomenon closely linked to the coherent emission process. PSR J0034—0721 is a bright, long-period ($P_2 = 0.943$ s) pulsar with dispersion measure $DM = 10.9$ pc cm$^{-3}$ that exhibits both subpulse drifting (Backer 1970; Huguenin et al. 1970) and extensive nulling (~45% of the time; Vivekanand 1995) and thus is an important object that can potentially reveal vital clues to the underlying emission mechanisms.

Subpulses are thought to represent “subbeams” caused by discrete emission regions that are stable over many pulsar rotations, which in some cases may be arranged in a “carousel” pattern centered on the magnetic dipole axis and rotating around it at some rate, $D$ (Ruderman & Sutherland 1975; Rankin 1986). Strong observational support for this view came with the work of Deshpande & Rankin (1999, 2001), who were able to determine that the regular drifter PSR B0943+10 has a stable carousel consisting of 20 discrete emission regions. One of the earliest and most successful emission models (Ruderman & Sutherland 1975) invoked $E \times B$ drift to explain the carousel’s circular motion; however, there are some outstanding issues with its quantitative predictions. First, the measured drift rate for at least some pulsars is known to be many times smaller than that predicted by $E \times B$ drift (e.g., Mitra & Rankin 2008). Second, the drift rate of some pulsars is not constant, but varies over time. The most common manifestation of this is the presence of temporally distinct drift modes, characterized by an abrupt change in the drift rate, usually with a timescale less than a single stellar rotation (e.g., Redman et al. 2005). Variations in drift rate can also occur over longer timescales, without sudden drift mode changes (e.g., Biggs et al. 1985; Bhattacharya et al. 2009). PSR J0034—0721 exhibits both long- and short-timescale drift rate variations, with three distinct drift modes designated as modes A, B, and C (Huguenin et al. 1970; Wright & Fowler 1981), and with drift rate variations occurring within each mode (Vivekanand & Joshi 1997).

The methodology of Deshpande & Rankin (2001) involves mapping the intensity sequences from the drifting subpulses onto a coordinate system centered on the magnetic axis (the so-called “cartographic transform”). Ideally, this can be applied to other drifters, such as PSR J0034—0721, allowing us to determine the geometry and dynamics of the emission regions. This is not always possible, mainly due to the difficulty in resolving the presence of aliasing, in which the true carousel drift rate is different from the measured drift rate because of the sub-Nyquist sampling of the emitting region due to the star’s rotation. A carousel with an integer number of subbeams admits only a discrete (but possibly infinite) set of solutions to any given observed drift band pattern, with higher drift rates corresponding to higher-order aliasing. Determining the true carousel rate, and hence the order of aliasing present, is difficult because different sets of parameter values (viewing geometry, as well as aliasing) can give rise to identical-looking drift bands. This is especially true for PSR J0034—0721, whose multiple drift modes complicate the issue, and whose viewing geometry is not precisely known (Smits et al. 2007).
Nevertheless, it is vital to resolve the aliasing order so we can understand the configuration of emission regions of this pulsar and the relationship between its three different drift modes.

The regularity of both the stellar rotation and the observed drift bands allows us to define a number of periodicities, often used in subpulse drifting analyses (e.g., Deshpande & Rankin 1999; Edwards & Stappers 2002). \(P_1\), \(P_2\), and \(P_3\) are respectively defined as (1) the pulsar’s rotation period, (2) the temporal separation between two subpulses within a single rotation, and (3) the time it takes for a subpulse to arrive at the same rotation phase as its predecessor. The drifting subpulses appear as diagonal drift bands in the pulse stack, which is the (one-dimensional) time series plotted in a two-dimensional array, with each row corresponding to 360° of rotation, and time progressing along the vertical axis (Figure 1). Visually, \(P_2\) and \(P_3\) are realized as the horizontal and vertical separations (respectively) of consecutive drift bands. The slope of the drift bands is the observed drift rate, defined as

\[
D = \frac{d\varphi}{dp} = \pm \frac{P_2}{P_3},
\]

where \(\varphi\) is the phase, \(p\) is the pulse number, and the sign indicates the drift direction.

Drift modes are usually characterized by their \(P_3\) value, which is generally found to remain stable over the course of a drift sequence (defined here as a set of contiguous pulses all belonging to the same drift mode). Early work on PSR J0034−0721 measured \(P_3\) values of 12.5, 6.8, and 4.5 \(P_1\) for modes A, B, and C, respectively (Huguenin et al. 1970; Wright & Fowler 1981), with individual drift sequences lasting from a few to hundreds of pulse periods (Vivekanand & Joshi 1997).

Interestingly, the subpulse phases appear to be correlated across the nulls (Joshi & Vivekanand 2000), indicating organized motion of the supposed carousel configuration even during nulls.

Smits et al. (2005, 2007) investigated the behavior of these drift modes at nine frequencies ranging from 157 MHz to 4.85 GHz. Their analysis revealed that the drift bands of mode B were largely undetectable at the higher frequency. They offered a geometric interpretation, placing the surface plasma events during mode B emission closer to the magnetic pole than the mode A plasma events. The assumed radius-to-frequency mapping implies that at higher frequencies, the mode B emission forms too narrow an emission cone to intersect the line of sight. The physical cause of the change of magnetic latitude of the surface plasma events, however, was not explored.

Indeed, no physical explanation has been offered for several key properties of PSR J0034−0721’s drift modes, such as their average duration, the order in which they appear, their relationship to the null sequences, and the variation (albeit small) in their respective \(P_3\) measurements. Crucially, the presence or absence of aliasing in PSR J0034−0721 has not been determined; however, Smits et al. (2007) estimate the number of discrete emissions in the carousel to be about 9, under the assumption that aliasing is not present.

In this paper we present new observations of PSR J0034−0721 made with the Murchison Widefield Array (MWA; Tingay et al. 2013), a low-frequency precursor to the Square Kilometre Array. We attempt to characterize the pulsar’s observed drifting behavior in terms of a small number of parameters that remain constant over the course of individual drift sequences. The data acquisition and pre-processing are described in Section 2. Our analysis of the drift bands and the investigation of their time-varying behavior are described in Section 3. The theoretical implications of a variable drift rate are discussed in Section 4, and our conclusions are presented in Section 5.

2. Observations and Data Processing

The data were taken with the MWA, a low-frequency aperture array located in remote Western Australia. The MWA is now geared for high time resolution science, with the recently commissioned Voltage Capture System mode (VCS; Tremblay et al. 2015). The VCS enables the recording of the raw voltages from each of the MWA’s 128 tiles, which are downloaded from the site to the dedicated data storage facility at the Pawsey Supercomputing Centre.\(^5\)

We recorded 42 minutes (\(~18.5\) TB) of VCS data on 2016 January 19. The data were processed following a procedure similar to that of Bhat et al. (2016), which is summarized here. Calibration of the data was performed with the Real Time System software (D. A. Mitchell 2017, in preparation), using an observation of Pictor A taken immediately prior to the pulsar observation. Using the calibration solution, the raw voltages

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\(^5\) https://www.pawsey.org.au/
were phased up to form a pencil beam (~2° in diameter) on PSR J0034–0721. The resulting data set (stored in the PSRFITS format; Hotan et al. 2004) consisted of 24 × 1.28 MHz coarse frequency channels ranging from 169.60 to 200.32 MHz and a time resolution of 100 µs. The data from only the central 88 out of 128 (10 kHz) fine channels of each coarse channel were kept because of aliasing effects inherent in the polyphase filter bank, which attenuates the response of the antennas at the edges of the coarse channels. The best solution was found by calibrating on 115 out of the available 128 antenna tiles, so the data from the remaining tiles were rejected from the pulsar analysis.

Finally, the resulting frequency–time data were processed in DSPSR (Van Straten & Bailes 2011) and PSRCHIVE (Hotan et al. 2004) to produce a single-pulse archive and a time series. The time resolution of the time series was 0.921 ms, corresponding to 1024 phase bins across one pulsar period. The data set is of very high quality, with an average signal-to-noise ratio of ~9 per pulse (without excising null pulses), approximately a factor of 8.5 times higher than that of the same observation processed incoherently (i.e., with the signal power detected at each tile summed together), ~20% less than the theoretical expectation. This paper presents the first study of individual pulses for pulsar emission science undertaken with the MWA (but see, e.g., Oronsaye et al. 2015, for previous single-pulse studies with the MWA).

3. Subpulse Drifting Analysis

The analysis in this paper is aimed at exploring how the behavior of the drift bands of PSR J0034–0721 varies both between different drift modes and within individual drift sequences. We analyzed only data within the on-pulse window, which was chosen to fall between the first and last phase bins whose average flux densities were 4σ above the off-pulse noise (the noise statistics were obtained from phase bins more than 90° away from the profile peak). The pulse window was thus determined to be in the range −25° ≤ φ ≤ 33°, where the point φ = 0° was defined to be the center of the phase bin that contained the largest average flux density.

3.1. Determining the Drift Mode Boundaries

Traditional methods of drift mode analysis include the Harmonic Resolved Fluctuation Spectrum (HRFS; Deshpande & Rankin 2001) and the mathematically equivalent Two-dimensional Fluctuation Spectrum (Edwards & Stappers 2003). These methods are designed to measure \( P_2 \) and \( P_3 \) by means of Fourier analyses of the time series. The fluctuation spectra of pulsars with multiple drift modes will contain the Fourier components corresponding to the \( (P_2, P_3) \) pairs of each drift sequence and a delocalized component corresponding to the distribution of the drift modes, as can be seen, for example, in the HRFS of PSR B2303+30 (Redman et al. 2005). Because PSR J0034–0721 exhibits multiple drift modes and long-duration nulls, the components corresponding to the three drift modes are not easily resolved in the fluctuation spectra (e.g., Figure 8 of Karuppusamy et al. 2011). Any realistic measurement of \( P_2 \) and \( P_3 \) (and hence the drift rate) can therefore only be achieved by first determining the precise locations of the transitions between different drift modes and treating each drift sequence separately. For this pulsar, the drift modes appear to switch on a timescale no longer than a single rotation period, and so it becomes possible to associate each pulse with a distinct mode.

One can use the sliding two-dimensional fluctuation spectrum (Serylak et al. 2009) to obtain a map of temporal changes to the drift modes, but the coarse resolution inherent in the technique cannot resolve sudden changes on the timescales of individual pulses. We therefore followed the method of Smits et al. (2005), which measures the average \( P_3 \) in a candidate drift sequence by computing the phase-averaged power spectrum (PAPS), which is the sum of the amplitudes of the DFT at each phase bin. The beginning and ending boundaries of the drift sequence were then adjusted incrementally until the peak value in the PAPS divided by the rms of the rest of the PAPS was maximized. The resulting map of drift modes is shown in the top panel of Figure 2, and a summary table of drift mode statistics is given in Table 1.

The distribution of drift modes in the MWA observation strongly resembles that of Smits et al. (2005, 2007), who observed the pulsar for a similar length of time at similar frequencies (157, 243, 325 MHz and above). In particular, we note the following similarities: mode A sequences are generally longer than modes B and C, and mode A sequences are often sandwiched between two mode B sequences with minimal nulling between them.

3.2. Linear Fits to Drift Bands

The simplest way to characterize individual drift bands is to treat them as independent line segments. By fitting a line to each drift band, we hope to assess whether there are any systematic changes in the drift rate over the course of a drift sequence.

Each pulse was convolved with a narrow Gaussian (FWHM = 2° ≈ 10% of \( P_2 \)) in order to smooth out high-frequency noise fluctuations. The phase bin containing the most power in each pulse was identified, and the phase of the interpolated peak (using a cubic spline to get a sub-bin estimation) was taken as the phase of a subpulse. \( P_2 \) has previously been measured to be ~20° at low frequencies (e.g., Smits et al. 2007), so the second highest peak was identified with the same method, but with the constraint that it was not closer than 10° to the first bin. For the vast majority of pulses, a maximum of two drift bands were visible in any given pulse, so we did not attempt to find a third subpulse peak.

An algorithm was designed to find connected series of subpulse peaks that belong to the same drift band. Starting at the beginning of the observation, and assuming that the subpulses found in the first pulse do in fact “belong” to genuine drift bands, we assigned the subpulses in the succeeding pulse to the already identified drift bands if the subpulse phases are within 10° of the drift band’s projected phase at the pulse in question. The projected phases were determined by a weighted least-squares fit to each subpulse already associated with a drift band, where the weighting was proportional to the peak amplitude of the subpulse. However, the variation in subpulse position requires that a statistically significant number of pulses be already assigned to a drift band in order to obtain a reliable extrapolation of the drift
Thus, if a drift band has so far only been assigned four subpulses or fewer, we assume a nominal drift rate\(^6\) of \(-2^\circ.5/P_2\) and only perform least-squares regression to find the phase offset. If a subpulse was found with a phase more than \(10^\circ\) to the right of the projected phases, it was assigned to the beginning of a new drift band. The process continues until the onset of a null sequence, and the entire algorithm is repeated for each drift sequence. The resulting assignment of subpulses to drift bands was checked by eye for correctness, and the same algorithm was successfully applied to the reverse time series to test it for robustness. Once all determined subpulses had either been assigned to a drift band or rejected as an outlier (if it did not fall within \(10^\circ\) of any projected drift band), the subpulse positions were fit by a weighted least-squares regression as before, except that this was also applied to even short (i.e., containing four or fewer subpulses) drift bands. The results of this algorithm for a subset of the pulse stack are illustrated by red lines in Figure 3.

\(^6\) For this pulsar, drift rates appear to range between approximately \(-0^\circ.5/P_2\) and \(-4^\circ.5/P_2\) as evident in the results.

The errors on the slopes of the drift bands are calculated to be

\[
m_{\text{unc}} = \frac{1}{n-2} \sqrt{\frac{\sum (w_i (\varphi_i - \bar{\phi})^2)}{\sum (w_i (p_i - \bar{p})^2)}},
\]

where the sums are iterated over the subpulses within a given drift band, \(n\) is the number of pulses within a drift band, \(\varphi\) and \(\bar{\phi}\) are the measured subpulse phase and the phase predicted from the linear fit, respectively, \(p\) is the pulse number, and \(\bar{p} = \frac{1}{n} \sum p_i\).

Having obtained a model for each drift band, we can now assess how the drift band slopes vary over the course of individual drift sequences (Figure 2, middle panel). Mode A drift bands tend to become steeper (i.e., the drift rate decreases), but those of mode B tend to become shallower (i.e., the drift rate increases), but not exclusively.

### 3.3. Quadratic Fits to Drift Bands

The linear fits to the drift bands suggest that the drift rate varies quasi-linearly over the course of each drift sequence (to a first-order approximation; see middle panel of Figure 2). Assuming that this is the case, and also assuming that \(P_2\) does not vary over time (consistent with what is observed in this data...
Table 1
Statistics of Drift Mode Measurements

| Mode | Number of Sequences | Mean $P_1$ (deg) | Mean $P_1$ (PAPS) ($P_1$) | Mean $P_3$ (Quad) ($P_1$) | Occurrence Fraction (%) | Mean Duration ($P_1$) |
|------|---------------------|------------------|---------------------------|---------------------------|------------------------|----------------------|
| A    | 9                   | 18.9 ± 1.1       | 11.9 ± 2.0                | 12.5 ± 0.8                | 18.4                   | 54.6                 |
| B    | 31                  | 19.8 ± 0.5       | 7.0 ± 0.5                 | 7.0 ± 0.2                 | 34.5                   | 29.6                 |
| C    | 2                   | 19.1 ± 2.9       | 5.9 ± 3.6                 | 4.6 ± 0.3                 | 0.8                    | 11.0                 |
| Null | 38                  | ...              | ...                       | ...                       | 45.5                   | 31.9                 |
| Unknown\(^a\) | 6   | 19.9 ± 3.2       | ...                       | ...                       | 0.8                    | 3.7                  |

Note. The mean $P_1$ values were measured in two ways: (1) the PAPS method of Smits et al. (2005) involves Fourier analysis of pulse stack columns and is described in Section 3.1; (2) the “Quad” method involves fitting quadratic lines to sets of drift bands and is described in Section 3.3. The mean errors are Gaussian-propagated from the standard deviations of the same quantities measured for individual drift sequences.

\(^a\) Sequences that were too short to yield a reliable measurement of $P_3$ were uncategorized.

The value of $P_2$ in PSR J0034–0721 is consistent with being constant in time, irrespective of drift mode (Smits et al. 2005; but see Vivekanand & Joshi 1997, for evidence of the contrary). However, it has been observed to decrease at higher observing frequencies, in accordance with the radius-to-frequency mapping (Cordes 1978; see our Figure 4 and references therein). Here, we report that $P_2$ is also dependent on

\[ \frac{d\varphi}{dp} = 2a_1p + a_2, \]

\[ P_2 = a_4, \]

\[ P_3 = \frac{P_2}{\frac{d\varphi}{dp}} = \frac{a_4}{2a_1p + a_2}. \]
the rotation phase, i.e., where the subpulses fall in the pulse window.

The average $P_2$ value is commonly measured by means of an autocorrelation function applied to the pulse stack. Here, we measure $P_2$ for each pulse individually, by simply taking the difference of phases of the two subpulse peaks detected by the peak-finding algorithm described in Section 3.2. The resulting $P_2$ measurements are plotted in Figure 6 against the average (absolute) phase of the two subpulses. There is a noticeable positive correlation between $P_2$ and (average) phase—i.e., subpulses at later phases are generally spaced more widely apart.

To confirm this trend, we performed the identical quadratic fits described above to smaller subsets of subpulses. Within each drift sequence, the subpulses were divided into three subsets, based on their absolute phases. The phase boundaries were not the same for each drift sequence; instead, they were chosen to ensure that the numbers of subpulses in each subset were the same (or differed only by one, if the total number of subpulses was not divisible by three). $P_2$, as measured by the fit parameter $a_2$ (see Equation (3)) for each subset, is shown plotted against the average phase of the subset in the right panel of Figure 6. A similar upward trend is evident. We note, in passing, that the three modes do not appear to be drawn from different distributions of $P_2$, which is contrary to the finding of Vivekanand & Joshi (1997), who reported a weakly negative correlation between $P_2$ and drift rate from analysis of their observations at 325 MHz.

### 4. Discussion

We have demonstrated the presence of two effects in PSR J0034$-$0721 that have previously not been studied in detail. First, the drift rate in PSR J0034$-$0721 varies gradually within individual drift modes, as well as sharply between them (Figure 2). Second, $P_2$ appears to be positively correlated with rotation phase, i.e., subpulses on the right-hand side of the pulse window (when viewed in the pulse stack) are more widely separated than those on the left-hand side (Figure 6).

Both of these effects were observed in PSR B0826$-$34 (Gupta et al. 2004, hereafter GGKS04), another long-period ($P_1 = 1.85$ s) drifter, although different from PSR J0034$-$0721 in many respects. PSR B0826$-$34 has a very wide profile, with up to 13 distinct drift bands being observed across all 360°. It appears to exhibit nulling, but weak emission (at the 2% level, at 1374 MHz) has been detected during null periods, enabling the tracing of the drift bands continuously over several hundred pulses (Esamdin et al. 2005). Bhattacharyya et al. (2008), however, report no emission during nulls (at the 1% level) in their observations at 157, 325, 610, and 1060 MHz. PSR B0826$-$34 and PSR J0034$-$0721 are suspected to have similar viewing geometries, with $\alpha$ (the angle between the rotation axis and the magnetic axis) and $\beta$ (the angle between the magnetic axis and the line of sight at closest approach) both being very small (<10°). The parameters $\alpha$ and $\beta$ are often estimated by fitting the polarization angle sweeps to the magnetic pole model (Radhakrishnan & Cooke 1969). However, for both pulsars, there are several combinations of $\alpha$ and $\beta$ that reproduced the observed polarization curve, and current estimates give 1.5 ≤ $\alpha$ ≤ 5°0 and 0°6 ≤ $\beta$ ≤ 2°0 for PSR B0826$-$34 (GGKS04) and $\alpha$ ≈ $\beta$ around 0°1 to 6°0 (Smits et al. 2007). A final difference is that, unlike PSR J0034$-$0721, whose drift rate always maintains the same direction and changes only gradually throughout any given drift sequence, the drift rate of PSR B0826$-$34 fluctuates about a mean value of ~0°/$P_1$, changing sign in a quasi-periodic manner.

#### 4.1. Variable Drift Rate by Stellar Surface Temperature Fluctuations

Given the apparent similarity with PSR B0826$-$34, we assess whether the explanations that GGKS04 offer for the appearance of these features in PSR B0826$-$34 would be applicable to PSR J0034$-$0721 as well. The variability of the drift rate is suggested to arise from fluctuations in the stellar surface temperature, which indirectly influences the $E \times B$ drift rate. Moreover, the apparent change in drift direction is attributed to an aliasing effect; with higher-order aliasing, the direction will appear to change if the true value of $P_1$ fluctuates over a small range that straddles an integral multiple of $P_1$. In this scenario, small fractional variations in the true drift rate can appear to observers as large fractional variations in measured

![Figure 4. Comparison of available measurements of $P_2$, with the panels from left to right showing measurements of modes A, B, and C respectively. The fact that $P_2$ is consistent with being uniform across all three modes at any given frequency suggests that the angular spacing of the emission regions around the magnetic axis does not change between mode switches.](image-url)
drift rate. GGKS04 calculate that only up to an 8% change in the true drift rate is required to explain the measured variation, and that this upper limit requires only a 0.14% fluctuation in the surface temperature.

Even though the observed drift rate in PSR J0034−0721 is ubiquitously unidirectional, the fractional variation is very large (≈67%) and can only be realistically explained by the same mechanism of fluctuating surface temperature if higher-order aliasing is invoked to bring the true drift rate variation down to a few percent. For the geometry assumed by Smits et al. (2005), with nine subbeams viewed at $\alpha \approx \beta \approx 4^\circ 5$, we find that the true drift rate becomes approximately $(10/k)\%$ for aliasing order $k \geq 1$. Thus, even aliasing order $k \geq 2$ would bring the true drift rate to a level consistent with the 8% inferred for PSR B0826−34. However, this cannot explain both the gradual change in drift rate within drift sequences and the abrupt change in drift rate between them, unless the temperature fluctuated at two distinct timescales. Even if aliasing is present, one is still left with a drift rate that is discontinuous at mode boundaries (see Esamdin et al. 2005, who point out the existence of cusps in the drifting pattern of B0826−34). Thus, in keeping with the observed timescale of drift rate variation observed in B0826−34 (~100 pulses $\approx 180\,$s), we surmise that if the surface temperature is indeed responsible for the intra-sequence drift rate variation, then some other, possibly unrelated mechanism must drive the drift mode changes.

It is of interest to know what the relationship is, if any, between the drift rates and carousel acceleration parameters of neighboring drift sequences. The presence of aliasing would obscure such a relationship, which suggests the possibility that the correct aliasing order and number of subbeams may be recognized by their ability to reveal a natural progression of carousel rotation parameters from one sequence to the next. This, however, requires a much longer data set than presented here since most drift sequences in PSR J0034−0721 are bordered by nulls (see Figure 2), and it is as yet unclear how the subpulse phase, drift rate, and carousel acceleration evolve during a null (Joshi & Vivekanand 2000). Based on the number of mode transitions in the present data set, we estimate a rate of approximately 40 suitable mode transitions (i.e., without intervening nulls) in 10,000 pulses, a conservative minimum required to investigate these relationships further.

4.2. The $P_2$ Dependence on Rotation Phase

GGKS04 invoke a new idea to explain the positive correlation between the measured $P_2$ and rotation phases. They suggest that the carousel pattern is centered not on the magnetic dipole axis, but around some other nearby axis (dubbed the “local pole”) that arises, perhaps due to a more dominant multipolar component near the surface. In their case, they were able to determine that a local pole that is offset from the dipole axis by $\sim 3^\circ$ is able to reproduce the observed $P_2$ dependence on rotation phase. We hope that a similar analysis will be able to find a local pole solution for PSR J0034−0721. This analysis, however, also depends on a known (or assumed) number of beams and aliasing order, which cannot yet be inferred from current observations.

Other explanations for this effect are not forthcoming. For example, aberration effects are traditionally invoked to explain the asymmetry in pulsar profiles, in which conal emission features are shifted to lower phases relative to core emission. Presumably, such effects are present in PSR J0034−0721, but due to the fact that its profile contains only a single (conal) component, they would not be detectable in the traditional way. However, any measurable feature with a dependence on rotation phase (such as $P_2$) should be “stretched” out at lower phases and “compressed” at higher phases, similarly to profile components (Gupta & Gangadhara 2003; Dyks et al. 2004). However, exactly the opposite is observed in the $P_2$ of PSR J0034−0721, so aberration effects cannot be invoked to explain it.

Another possible explanation is the motion of the visible point, as discussed by Yuen & Melrose (2014) and Yuen et al. (2016), which takes into account the direction of the dipolar magnetic field at the emission site, an effect that has traditionally been neglected in the interpretation of $P_2$ measurements. They showed that measurements of $P_2$ can dramatically underestimate the true subbeam separation when the angle between the rotation and magnetic axes, $\alpha$, is sufficiently small, which is believed to be the case for PSR J0034−0721 (e.g., Smits et al. 2005, 2007). However, they also showed that the discrepancy in $P_2$ is symmetrical about the fiducial point, with the measured $P_2$ increasing as one moves away (in either direction) from the fiducial point. Again, this is at odds with what is seen from our observations, where $P_2$ appears to increase monotonically across the pulse window.

Even though invoking the effect of a moving visible point may
explain the variation in $P_2$, it will require the assumption that the fiducial point lies somewhere to the left of the on-pulse region. However, attempts to constrain the fiducial point of PSR J0034−0721 have not met with success because of the difficulty of locating a zero-crossing point in the position-angle sweep of the dominant polarization, due to its flatness over the pulse window (Smits et al. 2007). Thus, we are not able to comment on the likelihood of this scenario.

5. Conclusion

We have conducted a detailed analysis of new observations of PSR J0034−0721 with the MWA at 185 MHz, a first-of-its-kind demonstration of this instrument’s capability of producing high-quality single-pulse data, in line with its intended science aims (Bowman et al. 2013). Our analysis shows that the drift bands of PSR J0034−0721 exhibit more complex behavior than what has been inferred from previous studies. In particular, (1) the measured drift rate changes continuously within individual drift sequences, with a characteristic variation timescale apparently longer than the typical duration of individual drift sequences; and (2) $P_2$ is positively correlated with rotation phase. Both of these effects were observed and studied in PSR B0826−34 by Gupta et al. (2004), who explain the variable drift rate by linking it to surface temperature fluctuations and the $P_2$ dependence on rotation phase by determining the position of a “local pole” around which the carousel is assumed to rotate. However, the applicability of their proposed physical explanations to PSR J0034−0721 requires the knowledge of the aliasing order and the number of subbeams in the carousel, which are currently unknown for PSR J0034−0721. However, we note that resolving the aliasing order and number of subbeams may be helped by assuming that the true drift rate varies continuously over drift mode boundaries, but such an investigation requires significantly longer observations than have been presented here.

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