A Study of the Multi-frequency Polarization Pulse Profiles of Millisecond Pulsars

(An ongoing PPTA paper)
Speaker: Shi Dai

(A very preliminary draft is attached with the presentation)
Motivations

• The first step of future projects
  – Freq evolution of pulse profile and freq-dependent timing
  – Stability of pulse profiles
  – Pulsar searching in radio continuum surveys (spectral index, fractional linear polarization...)

• An observationally-based publication
  (started by Alberto Mata)
  – Presenting high S/N, multi-freq, pol. profiles (make them available on the Internet)
  – Describing data sets and data analysis
  – Studying MSP physics...
Motivations

• Compared with Yan et al. 2011
  – An extra four pulsars;
  – More modern pulsar backend instrumentations;
  – Longer data sets enabling higher S/N ratio profiles;
  – Polarization pulse profiles in three independent bands (at 10, 20 and 50cm).
Motivations

• Compared with other previous works
  (e.g., Thorsett & Stinebring 1990; Navarro et al. 1997; Toscano et al. 1998; Kramer et al. 1998, 1999; Stairs et al. 1999; Manchester & Han 2004; Ord et al. 2004)
  – More modern pulsar backend instrumentations
  – Longer data sets and higher S/N:
    • More details of both profiles and PAs
    • Phase-resolved studies
    • Freq evolution within bands
Data analysis

- 10cm: PDFB4, 2008—2014;
- 20cm: PDFB3, 2008—2014;
- 50cm: CASPSR, 2011—2014;
- Median-filtered each sub-integration and removed 5 per cent of each edge of the bandpass;
- Flux and pol. Calibration (20cm: pcm calibration);
- DM: nominal DM from PPTA parfiles;
- RM: according to Yan et al. 2011; ionosphere contribution corrected using iri2012 (did not measure RM).
Data analysis

• To add the data in time to form a final mean profile, pulse times of arrival were obtained for each obs.

• Then pulsar spin, astrometric and binary parameters, and also harmonic waves are fitted if necessary to give white timing residuals for each pulsar.

• Finally, the separate observations were summed using this timing model.

• Weighted profile: psrwt ---- weighted by (S/N)^2

• Unweighted profile: to calculate spectral index...
Data analysis

• Pulse profile alignment:
  – Same technique as pulsar timing, according to Taylor 1992.
  – 10/50cm profiles are aligned with respect to that of 20cm.

➤ Phase-resolved analysis...
• Pulse width:
  
  – Compared with Yan et al. (2011b), 15 MSPs show overall width increase, and on average increases by \(~ 22\) per cent.
• Pulse width:
  
  – Compared with Yan et al. (2011b), 15 MSPs show overall width increase, and on average increases by ∼ 22 per cent — weak components and emissions that unknown for PSRs J2145−0750, J1603−7202 and J2241−5236.
  
  – No strong evidence that the pulse width (W10 and W50) decreases as the frequency increases.
  
  – Average width of components:

    $$W_c = \frac{\text{Overall width}}{\text{No. of component}}$$

    1. $W_c$ v.s. period
    2. MSPs v.s. normal pulsars
• **Spectral index:**
  
  – Average spectral index: can be fit by one power-law, $\alpha = -1.8 \pm 0.1$

Some MSPs deviate from a simple pow-law, e.g., J1713, J1600
• Spectral index:
  – Phase-resolved spectral index

  ✓ Showing similar components as the mean pulse profiles. Different components of the profile often have different spectral indices.

  ✓ Significantly deviating from the average spectral index.
• Spectral index:
  – Phase-resolved spectral index

✓ Showing similar components as the mean pulse profiles. Different components of the profile often have different spectral indices.

✓ Significantly deviating from the average spectral index.

✓ For some MSPs, some part of their spectral indices have larger uncertainties, which indicates that their spectra can not be well fitted with a simple power-law.
• Polarization:
  – Evidences of new orthogonal transitions (e.g., J0437, J0711...); and new non-orthogonal transitions (e.g., J1045...)
  – No clear evidence that the fractional linear pol. shows simple frequency evolution, and so does the fractional circular pol. and fractional net circular pol.
• Polarization:
  – Pre-cursors and post-cursors have higher fractional linear pol? (e.g., J1603, J1939, J2145 and J2241; however, we don’t see such feature for J1744)
- The orthogonal and non-orthogonal mode transitions appear when the linear polarization are weak.
- The phase-resolved fractional linear polarization shows good correlation across bands.
Discussion

• We need more ideas!!!
  – Frequency evolution of profile and polarization parameters
  – Implications of phase-resolved spectral index and fractional linear polarization
  – General discussion on MSP physics
  – ......
Next steps…

1. Freq-dependent timing
   - Algorithm (Pennucci et al. 2014, Liu et al. 2014)
   - Simulation: profile evolution + scintillation
   - Application on real data sets

2. The stability of pulse profile
   - To understand why freq-dependent timing doesn’t work
   - ToA out-layers
   - RFI
A Study of the Multi-frequency Polarization Pulse Profiles of Millisecond Pulsars

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\textsuperscript{12}August 2014

\textbf{ABSTRACT}

We present high signal-to-noise ratio, multi-frequency polarization profiles for 24 millisecond pulsars that are being observed as part of the Parkes Pulsar Timing Array (PPTA) project. The pulsars are observed in three bands, centering at 728, \( \sim \)1369 and 3100 MHz, using a dual-band 10cm/50cm receiver and the central beam of the 20cm multibeam receiver. Data sets that have been carefully calibrated over several years are utilized, which allows us to study the components and evolution of profiles with frequency, and to show previously undetected profile features. At 1400 MHz, compared with previous results, the overall pulse width increases by \( \sim \)22 per cent on average, and 17 of the 24 pulsars show emission over more than half of the pulse period. The morphology of pulse profiles shows clear frequency evolution, but the pulse widths are relatively constant with frequency. The phase-resolved spectral indices show structures following the components of pulse profiles and the values significantly deviate from the mean spectral index. We do not see simple frequency evolution of the polarization parameters, but there are evidences that pre-cursors and post-cursors have higher fractional linear polarization.

\textbf{Key words:} pulsars: general

\section{INTRODUCTION}

Millisecond pulsars (MSPs) are a special subgroup of radio pulsars. Compared with “normal” pulsars, they have much shorter spin periods and smaller spin-down rates, and therefore have larger characteristic ages and weaker implied dipole magnetic fields. The short spin periods and highly stable average pulse shapes of MSPs make them powerful tools
to investigate various astrophysical phenomena using high precision timing of the pulse arrival times (e.g., Manchester 2008).

The Parkes Pulsar Timing Array (PPTA) project (Manchester et al. 2013) regularly observes 24 MSPs. The main goal of the project is to identify slight variations in the pulse arrival times from these MSPs that can be identified as being caused by gravitational waves passing through the solar system. The search for gravitational waves has been described in other papers (recent work includes Shannon et al. (2013), Wang et al. submitted to MNRAS, Zhu et al. submitted to MNRAS).

We have not yet detected gravitational waves. In order to do so we can observe a larger set of pulsars, increase the span of the observations and/or to increase the timing precision achieved for each observation. Determining how to improve the timing precision and how much we can improve it relies on our understanding of the stability of pulse profiles (e.g., Shannon et al. 2014) and also the frequency evolution and polarization properties. For our work we study the large number of well calibrated, high signal-to-noise ratio (S/N) multi-frequency polarization profiles that have been obtained as part of the PPTA project.

An earlier analysis of the pulse profiles from the PPTA sample was published by Yan et al. (2011b). This earlier work is extended in this paper as: (1) we include an extra four pulsars that have been recently added to the PPTA sample; (2) we use more modern pulsar backend instrumentation than was available to Yan et al. (2011b); (3) we use larger data sets enabling higher S/N ratio profiles; (4) we provide polarization pulse profiles in three independent bands (at 10, 20 and 50cm). Yan et al. (2011b) only analysed observations in the 20cm band. We note that we have mainly the same sample of pulsars as was described by Yan et al. (2011b), but our data sets are independent (i.e., no data is in common between this and the earlier publication).

It has been shown that, compared with normal pulsars, the pulse profiles of MSPs are much more complicated and cover a much larger fraction of the pulse period (Yan et al. 2011b), and the PAs are more complex and do not fit the ‘rotating vector model’ (RVM, Radhakrishnan & Cooke 1969). However, the spectra of MSPs and normal pulsars are similar (Toscano et al. 1998; Kramer et al. 1998, 1999a), and both of them have features such as high degrees of linear polarization and orthogonal mode position angles (PA) jumps (see e.g., Thorsett & Stinebring 1996; Navarro et al. 1997; Stairs et al. 1999; Manchester & Han 2004; Ord et al. 2004). To explain the complex pulse profiles, multiple emission cones were proposed and discussed by several authors (Rankin 1993; Kramer 1994; Gupta & Gangadhara 2003). An alternative model suggests that the emission beam of a pulsar is filled with randomly distributed emission patches (Lyne & Manchester 1988; Manchester 1993; Han & Manchester 2001). The patchy model may explain more complicated multi-component and asymmetric pulse profiles.

To date, no simple model exists yet that can describe the observations. This paper is the first in a series of papers that we hope will shed new light on the MSP emission mechanism. This first paper is purposely an observationally-based publication. We present the new profiles in the various observing bands and describe how they were created.

We determine various observationally-derived properties of the profiles (such as spectral indices, polarisation fractions, etc.) and study how such parameters vary between pulsars and also for different components for a given pulsar. The data described here will be used in a subsequent paper to study the stability of the pulse profiles as a function of time. This sample of pulsars has been chosen for high-precision pulsar timing experiments. In a further paper, we will therefore also test out new methods (e.g., Pennucci et al. 2014; Liu et al. 2014) to improve our timing precision using frequency-dependent pulse templates. Our data sets are publicly available enabling anyone to compare the actual observations with their models of the pulse profiles.

Details of the observation, data processing and data access are given in Section 2. Multi-frequency polarization profiles of each MSPs are presented in Section 3. In Section 4, we measure the pulse width at different frequencies. In Section 5, we present results of flux densities and spectral indices. In Section 6, the polarization parameters at different frequencies are shown. The implications of the results are discussed in Section 7.

2 OBSERVATIONS AND ANALYSIS

2.1 Observations

We selected observations from the PPTA project, which includes observations of 24 MSPs. The pulsars are observed regularly, with an approximate observing cadence of three weeks, in three bands centred close to 730, 1400 and 3100 MHz, using a dual-band 10cm/50cm receiver and the central beam of the 20cm multibeam receiver. In each of the bands, the observing bandwidth was 64, 256 and 1024 MHz, respectively. We used both digital polyphase filterbank spectrometers (PDFB4 at 10cm and PDFB3 at 20cm) and a coherent dedispersion machine (CASPSR at 50cm). In Table 1, we summarize the observational parameters for the 24 PPTA MSPs. For each band of the MSPs, we present the number of frequency channels across the band, the number of bins across the pulse period, the total number of observations we used and the total integration time.

To calibrate the gain and phase of the receiver system, a linearly polarized broad-band and pulsed calibration signal is injected to the two orthogonal linearly polarized probes through a calibration probe at 45° to the signal probes. The pulsed calibration signal was recorded for 2 min prior to each pulsar observation. Signal amplitudes were placed on a flux density scale using observations of Hydra A. All data were recorded using the PSRFITS data format (Hotan et al. 2004) with 1-min subintegrations and the full spectral resolution. (For further details see Manchester et al. (2013), and references therein).

2.2 Analysis

The data were processed using the PSRCHIVE software package (Hotan et al. 2004). To excise radio-frequency interference, we median-filtered each sub-integration and removed 5 per cent of each edge of the bandpass. The polarization was then calibrated by correcting for differential gain.
The Stokes parameters were in accordance with the astronomical conventions described by van Straten et al. (2010). Stokes $V$ is defined as $I_{\text{LH}} - I_{\text{RH}}$, using the IEEE definition for sense of circular polarization. Stokes $L$ was calculated as $L = (Q^2 + U^2)^{1/2}$, and the noise bias in $L$ was corrected according to Lorimer & Kramer (2005), and the similar bias in $V$ was corrected as described in Yan et al. (2011b). PAs were calculated as $\psi = 0.5 \tan^{-1} (U/Q)$, which are absolute and measured from celestial north towards east, i.e. counterclockwise on the sky. The error of PA was estimated according to Everett & Weisberg (2001), and the PA curve is plotted only when the linear polarization is greater than 4 $\sigma$. The baseline region was computed for all four Stokes-parameter profiles, separately, and baselines for each of the Stokes parameter profiles were set to zero mean.

Table 1. Observational parameters for the 24 PPTA MSPs.

<table>
<thead>
<tr>
<th>PSR</th>
<th>No. of channels</th>
<th>No. of phase bins</th>
<th>No. of observation epochs</th>
<th>Integration time</th>
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</table>

and phase between the receptors using associated calibration files. For 20 cm observations with the Multibeam receiver, we corrected for cross coupling between the feeds through a model derived from observations of PSR J0437−4715 that covered a wide range of parallactic angles.

In order to add the data in time to form a final mean profile, pulse times of arrival were obtained for each observation using an analytic template based on an existing high S/N pulse profile. The TEMPO2 pulsar timing package (Hobbs et al. 2006) was then used to fit pulsar spin, astrometric and binary parameters, and also fit harmonic waves if necessary to give white timing residuals for each pulsar. Finally, the separate observations were summed using this timing model to determine relative phases and form the final Stokes-parameter profiles.

To give the best possible S/N in the polarization pulse profiles, the individual observation profiles were weighted by their (S/N)$^2$ when forming the sum profile. We also produced unweighted profiles and use them to investigate the phase-resolved spectral index and fractional linear polarization in Section 4.

To form mean polarization profiles, the Faraday rotation across the band should be corrected. According to Yan et al. (2011a), the interstellar rotation measure (RM) of PPTA MSPs are stable, and we used interstellar RM values from Yan et al. (2011b). To account for the contribution of the Earth’s ionosphere, we used the International Reference Ionosphere (IRI) model suggested in Yan et al. (2011a). Recently, another model based on the Global Positioning System (GPS) has been used by Sotomayor-Beltran et al. (2013).

In Table 2 we present basic pulsar parameters for the 24 MSPs from the ATNF Pulsar Catalogue (Manchester et al. 2005). For each observing band, we also present the dispersion smearing and the pulse broadening time caused by scattering (in units of profile bins). The dispersion smearing across each frequency channel is calculated according to,

$$\Delta f_{DM} \approx 8.30 \times 10^{6} \text{ DM } \Delta f^{-3} \text{ ms},$$

where $\Delta f$ is the channel width in MHz, $f$ is the band centre frequency in MHz, and the DM is in units of cm$^{-3}$ pc.
The pulse broadening time caused by scattering is estimated using the empirical fit from Bhat et al. (2004).

\[ \log \tau_d = -6.46 + 0.154 \log DM + 1.07(\log DM)^2 \]

\[ - (3.86 \pm 0.16) \log \left( \frac{f}{1000} \right) \text{ ms.} \] (2)

We note that in Table 2, we only list \( \tau_d \) values that are \( \geq 0.01 \) bin and set others as zero.

2.3 Pulse profile alignment

To investigate, for each MSP, the frequency evolution of pulse profile across bands, we align the average profile in the 10 and 50cm bands with respect to that in the 20cm band. The technique we are using is described in detail in Taylor (1992), which was originally developed for the measurement of pulse arrival times.

2.4 Data access

The raw data and calibration files used in this paper are available from the Parkes data archive (Hobbs et al. 2011, data.csiro.au). The scripts used to create the results given in this paper and the resulting averaged profiles are available for public access from XXX (Note to referee: we intend to make these data available from the data archive - however, once published we cannot change the files and therefore we will only make them available when the paper is accepted for publication.).

3 MULTI-FREQUENCY POLARIZATION PROFILES

In this section, we present and discuss the multi-frequency polarization profiles of each MSP. Associated with polarization profiles in each band, we also show the PA variations and a zoom-in of the baseline for each pulsar. We discover weak components and emissions that unknown for PSRs J1045--0750, J1603--7202 and J2241--5236. We also show new details of the PA curves, including new orthogonal transitions for PSRs J0437--4715, J0711--6830, J1643--1224, J2145--0750, J1603--7202 and J2241--5236; and new non-orthogonal transitions for PSRs J1045--4509, J1857+0943 and J2124--3358.

3.1 PSR J0437--4715

The top panel of Fig. 1 shows the polarization pulse profiles of the strongest PPTA MSP, PSR J0437--4715. At 1369 MHz, our results are in good agreement with previously published results (Ord et al. 2004; Yan et al. 2011b). Our high S/N profiles provide more details in the PA curve, and we show that the PA curves are complex and very different in three bands. At 1369 MHz, the discontinuous PA at the leading edge of the trailing component reported by Yan et al. (2011b) is not observed, and the PA curve seems to be continuous. The main pulse of the profile shows clear frequency evolution, and most significantly, the trailing peak becomes much stronger at low frequencies relative to the rest of the profile. It splits into two peaks as previously observed by Stairs et al. (1999). From the high frequencies to low frequencies, the fractional linear polarization increases, and the trailing component becomes highly linear polarized. At 728 MHz, the circular polarization swaps sign compared to higher frequencies.

3.2 PSR J0613--0200

The middle panel of Fig. 2 shows the polarization pulse profiles of PSR J0613--0200. At 1369 MHz, our results are in good agreement with previously published results (Ord et al. 2004; Yan et al. 2011b). Our high S/N profiles provide more details in the PA curve, and we show that the PA curves are complex and very different in three bands. At 1369 MHz, the discontinuous PA at the leading edge of the trailing component reported by Yan et al. (2011b) is not observed, and the PA curve seems to be continuous. The main pulse of the profile shows clear frequency evolution, and most significantly, the trailing peak becomes much stronger at low frequencies relative to the rest of the profile. It splits into two peaks as previously observed by Stairs et al. (1999). From the high frequencies to low frequencies, the fractional linear polarization increases, and the trailing component becomes highly linear polarized. At 728 MHz, the circular polarization swaps sign compared to higher frequencies.

3.3 PSR J0711--6830

The bottom panel of Fig. 3 shows the polarization pulse profiles of PSR J0711--6830. At 1369 MHz, our results are in good agreement with previously published results (Ord et al. 2004; Yan et al. 2011b). The double-peaked weak component following the second peak is clear. The orthogonal mode transition after the peak of the leading component is confirmed, and possible orthogonal mode transitions at the trailing edge of the main peak are observed at 1369 MHz and disappear at lower frequencies. Except for that at lower frequencies, the leading component becomes stronger relative to the main pulse and the fractional linear polarization of the main peak increase significantly, the frequency evolution of the profile is not significant.

3.4 PSR J1017--7156

The top panel of Fig. 4 shows the polarization pulse profiles of PSR J1017--7156. Our results are in good agreement with, and extend, previously published results (Keith et al. 2012). We show that the PA variations are more complex than was observed in previous work. Both the linear and circular polarization shows significant evolution with frequency, and the circular polarization close to phase 0 swaps sign at 728 MHz. The trailing emission becomes stronger at higher frequencies.

3.5 PSR J1022+1001

The middle panel of Fig. 5 shows the polarization pulse profiles of PSR J1022+1001. Our results are in good agreement with previously published results (Kramer et al. 1999b; Stairs et al. 1999; Ord et al. 2004; Yan et al. 2011b). The...
Figure 1. Multi-frequency polarization profiles for PSR J0437−4715. The right-side panels present the total intensity $I$ (black, blue and red line for the 3100, 1369 and 728 MHz band, respectively, as indicated), linearly polarized intensity $L$ (brown line) and circularly polarized intensity (grey line). On the left side of each profile, the PA of the linearly polarized emission and the low-level details of the polarization profiles are shown. The lower part of the left panel shows the phase-resolved spectral index. The red dashed line represents the average spectral index with its uncertainty indicated by the yellow region. The lower part of the right panel shows the phase-resolved fractional linear polarization, and the black, blue and red points represent the 3100, 1369 and 728 MHz band, respectively. The yellow dashed line represents the average fractional linear polarization.
<table>
<thead>
<tr>
<th>PSR</th>
<th>( P ) (ms)</th>
<th>DM (cm(^{-3}) pc)</th>
<th>DM smear (bin)</th>
<th>( \tau_d ) (bins)</th>
</tr>
</thead>
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**Table 2.** Pulsar parameters for the 24 PPTA MSPs.

PA variation generally fits the RVM in all three bands, but near the centre of the profile, it is discontinuous in the 10cm bands and shows discontinuities in the 20cm and 50cm bands as reported by Yan et al. (2011b). The relative strength of the two main peaks evolves dramatically with frequency. While the second peak keeps highly linearly polarized, the first peak depolarizes rapidly.

### 3.6 PSR J1024−0719

The bottom panel of Fig. 6 shows the polarization pulse profiles of PSR J1024−0719. At 1369 MHz, our results are in agreement with previously published results by Yan et al. (2011b). The relative strength of the two main peaks evolves dramatically with frequency. While the second peak keeps highly linearly polarized, the first peak depolarizes rapidly.

### 3.7 PSR J1045−4509

The top panel of Fig. 7 shows the polarization pulse profiles of PSR J1045−4509. At 1369 MHz, our results are generally consistent with previously published results by Keith et al. (2012). The PAs are flat over the main pulse, but show variations over the leading and trailing emissions.

### 3.8 PSR J1446−4701

The middle panel of Fig. 8 shows the polarization pulse profiles of PSR J1446−4701. At 1369 MHz, our results are generally consistent with previously published results by Yan et al. (2011b). The PA of the low-level bridge emission seems to be discontinuous with the rest of the PA variations and could be an orthogonal transition. Except for that at low frequencies, the peak at the trailing edge of the main peak disappears and the fractional linear polarization of the trailing emission decreases, the profile evolution is not significant.

### 3.9 PSR J1545−4550

The bottom panel of Fig. 9 shows the polarization pulse profiles of PSR J1545−4550. At 1369 MHz, Burgay et al. (2013) shows a component around phase 0.35 that we do not see in our analysis. We have confirmed with the High Time Resolution Universe (HTRU) collaboration that this extra component was caused by an error in their analysis. Apart from this, our profiles are consistent in all three frequency bands.
We also show that the low-level emission extend over at least 80 per cent of the pulse period.

3.10 PSR J1600–3053

The top panel of Fig. 10 shows the polarization pulse profiles of PSR J1600–3053. At 1369 MHz, our results are generally consistent with previously published results (Ord et al. 2004; Yan et al. 2011b). The leading component of the main pulse becomes weaker at low frequencies relative to the main
peak. The central part of the pulse profile depolarizes rapidly as frequency goes down. We see a sign swap of the circular polarization between 3100 and 1369 MHz, and at 728 MHz, the circular polarization becomes almost zero across the whole profile.

3.11 PSR J1603−7202

The middle panel of Fig. [11] shows the polarization pulse profiles of PSR J1603−7202. At 1369 MHz, our results are in good agreement with previously published results (Ord et al. 2004; Yan et al. 2011b). The broad low-level feature preceding the main pulse and the double-peak

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**Figure 3.** Multi-frequency polarization profiles for PSR J0711−6830. See Fig. [1] for further details.
A Study of the Multi-frequency Polarization Pulse Profiles of Millisecond Pulsars

trailing pulse can be clearly identified. We find that there are low-level emissions connecting the main pulse and the double-peak trailing pulse. The relative strength of the two main peaks evolves significantly with frequency. As frequency goes down, the second main peak becomes highly circular polarized, and the low-level emissions almost disappear.

3.12 PSR J1643−1224

The bottom panel of Fig. 12 shows the polarization pulse profiles of PSR J1643−1224. At 1369 MHz, our results are in good agreement with, and extend, previously published results (Ord et al. 2004; Yan et al. 2011b). The PA of the broad feature preceding the main pulse is determined and
Figure 5. Multi-frequency polarization profiles for PSR J1022+1001. See Fig. 4 for further details.

found to be not only discontinuous with the rest of the PA variation, but also show an orthogonal transition. While the linear and circular polarization show clear frequency development, the total intensity does not evolve with frequency significantly.

3.13 PSR J1713+0747

The top panel of Fig. 13 shows the polarization pulse profiles of PSR J1713+0747. At 1369 MHz, our results are consistent with previously published results (Ord et al. 2004; Yan et al. 2011b), showing the almost complete linear polarized leading and trailing components. We detect weak emis-
Figure 6. Multi-frequency polarization profiles for PSR J1024−0719. See Fig. 1 for further details.

The linear polarization of the leading and trailing components become stronger at low frequencies relative to the rest of the profile.

References:
- Van et al. (2011b)
Figure 7. Multi-frequency polarization profiles for PSR J1045−4509. See Fig. 1 for further details.

3.14 PSR J1730−2304

The middle panel of Fig. 14 shows the polarization pulse profiles of PSR J1730−2304. At 1369 MHz, our results are consistent with previously published results (Ord et al. 2004; Yan et al. 2011b). We clearly show the weak leading and trailing components already reported, and detect a weaker leading component not discovered before. This increases overall width of the pulse from 232° to 248°. The pulse profile is very complex, with four clear peaks across the main pulse. The relative strength of these four peaks changes dramatically in different bands. While at 3100 MHz the second peak is the strongest, at 728 the third becomes stronger. As the frequency goes down, the second peak depolarizes...
A Study of the Multi-frequency Polarization Pulse Profiles of Millisecond Pulsars

Figure 8. Multi-frequency polarization profiles for PSR J1446–4701. See Fig. 1 for further details.

rapidly. The PA variations is also complex and are very different in the three bands.

3.15 PSR J1744–1134

The bottom panel of Fig. 8 shows the polarization pulse profiles of PSR J1744–1134. At 1369 MHz, our results are consistent with previously published results (Yan et al. 2011b). The multiple-component precursor is clearly identified and no significant post-cursor component is observed.
While the PAs of the main pulse show a smooth decrease, those of the precursor have clear structures and do not simply connect with the rest of the PA variations. The shape of the PA curves are similar in three bands. The main pulse is highly linearly polarized from 728 to 3100 MHz. The circular polarization of main pulse grows stronger from 3100 to 1369 MHz, but diminishes at 728 MHz.

3.16 PSR J1824–2452A

The top panel of Fig. 16 shows the polarization pulse profiles of PSR J1824–2452, which is in the globular cluster M28 (Lyne et al. 1987). At 1369 MHz, our results are consistent with and extend previously published results (Yan et al. 2011b). The weak component around phase −0.4 is clearly...
shown and is highly linearly polarized. At 1369 MHz, we also show that there are low-level bridge emissions connecting the two main components of the pulse profile. The PAs of preceding components are continuous themselves, but are discontinuous with the rest of the PA variations. The frequency evolution of the total intensity is significant. The first main peak observed at 1369 MHz and the trailing component grow rapidly relative to rest of the profile as frequency goes down, while the leading component diminish at low frequencies.
3.17 PSR J1832−0836

The middle panel of Fig. 17 shows the polarization pulse profiles of PSR J1832−0836. At 1369 MHz, our results are consistent with, and extend, previously published results [Burgay et al. 2013]. The components around phase −0.45 and −0.08 are highly linearly polarized. The PAs around phase −0.05 and 0.3 seem to be discontinuous, but is hard to confirm because of the low S/N.
3.18 PSR J1857+0943

The bottom panel of Fig. 12 shows the polarization pulse profiles of PSR J1857+0943. At 1369 MHz, our results are generally consistent with previously published results (Yan et al. 2011b). We show more details of the PA variation, which is very complex and inconsistent with the RVM. At the leading edge of the main pulse, the PA decreases rapidly followed by an orthogonal mode transition. Around phase 0.05, there is evidence of a non-orthogonal transition. Close to the peak of the interpulse, the PA shows a discontinuity at 1369 MHz, but becomes continuous at 3100 MHz. Both the main pulse and the interpulse have multiple components and evolve with frequency, and at 728...
MHz there is a new linear polarization component appearing close to the center of the main pulse.

### 3.19 PSR J1909−3744

The top panel of Fig. [19] shows the polarization pulse profiles of PSR J1909−3744. At 1369 MHz, our results are generally consistent with results of [Ord et al. (2004); Yan et al. (2011b)], showing a narrow main pulse and a weak feature preceding the main pulse by about 0.45 in phase. The fre-

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**Figure 13.** Multi-frequency polarization profiles for PSR J1713+0747. See Fig. [1] for further details.
A Study of the Multi-frequency Polarization Pulse Profiles of Millisecond Pulsars

Figure 14. Multi-frequency polarization profiles for PSR J1730−2304. See Fig. 1 for further details.

The middle panel of Fig. 20 shows the polarization pulse profiles of PSR J1939+2134. At 1369 MHz, our results are generally consistent with previously published results (Yan et al. 2011b). As explained in Yan et al. (2011b), because of the high DM/P, our observations are significantly
affected by DM smearing, and we do not see the secondary maxima at the trailing edges of both the main pulses and interpulse (Thorsett & Stinebring 1990; Stairs et al. 1999; Ord et al. 2004). We confirm the existence of weak components preceding both the main pulse and interpulse and show that they are highly linear polarized, and therefore rule out the possibility of undetected RFI or instrumental problems. Our results show stronger left-circular emission in the main pulse compared to Yan et al. (2011b). The interpulse becomes stronger relative to the main pulse at lower frequencies. The fractional linear polarization of the main pulse increases significantly as frequency decreases while that of the interpulse decreases.

Figure 15. Multi-frequency polarization profiles for PSR J1744−1134. See Fig. 1 for further details.
3.21 PSR J2124−3358

The bottom panel of Fig. 21 shows the polarization pulse profiles of PSR J2124−3358. At 1369 MHz, the complex profile we show here is generally consistent with previously published results (Yan et al. 2011b). We are able to provide more details of the PA variation and show that it has complex structures. At 1369 MHz, around phase 0.03 and −0.5, there are evidences of two orthogonal mode transitions. At 3100 MHz, around phase 0.1, there is a non-orthogonal transition of ∼ 120°. The frequency evolution of pulse profile is relatively weak, but we can still see that the trailing edge of the main pulse becomes stronger at lower frequencies and the main peak splits into two peaks. The fractional linear
Figure 17. Multi-frequency polarization profiles for PSR J1832−0836. See Fig. 1 for further details.

polarization of the main pulse increases at lower frequencies.

3.22 PSR J2129−5721

The top panel of Fig. 17 shows the polarization pulse profiles of PSR J2129−5721. At 1369 MHz, our results are in good agreement with and extend previously published results (Yan et al. 2011b). The weaker leading shelf of emission extends to at least phase of −0.4, and the post-cursor
clearly has multiple components. We show more details of PA in the trailing edge of the main pulse. The PA decrease across the main pulse, and then increase quickly followed by an orthogonal mode transition. From high frequencies to low frequencies, the trailing main-pulse component diminishes rapidly, and the second component of the main pulse becomes stronger than the first component. The fractional linear polarization of the main pulse increases as frequency decreases.
3.23 PSR J2145−0750

The middle panel of Fig. 23 shows the polarization pulse profiles of PSR J2145−0750. At 1369 MHz, our results are in good agreement with and extend previously published results [Yan et al. 2011b]. Around phase 0.4, there are evidences of low-level emissions which significantly extends the overall width of this MSP from 187° to 277°. At 728 MHz, a new discontinuous feature appears at the trailing edge of the main peak. The trailing emission and the weak leading component become stronger relative to the main pulse at lower frequencies, but the PA curves are generally similar in three bands.
Figure 20. Multi-frequency polarization profiles for PSR J1939+2134. See Fig. 1 for further details.

3.24 PSR J2241–5236

The bottom panel of Fig. 24 shows the polarization pulse profiles of PSR J2241–5236. At 1369 MHz, our results generally agree with, and extend, previously published results [Keith et al. 2011]. We show a new low-level component around phase 0.4 with a width of $\sim 0.2$. We also show more details of the complex PA variations and there are evidences of two orthogonal mode transitions close to the peak. The frequency evolution of pulse profile is hard to see, but the fractional linear polarization increases at lower frequencies.
4 Pulse Width

In Table 3, we present the overall pulse width and pulse widths at 50 per cent of the peak flux density (W50) and 10 per cent of the peak (W10), all in degrees of longitude, where 360 is equivalent to the pulse period or 1.0 in pulse phase, and in milliseconds. The overall pulse width is measured from the first point to the last point where the pulse intensity significantly exceeds the baseline noise (Yan et al. 2011b), with pulse profiles in the 20 cm band since they normally have the highest S/N.

In Fig. 25, we show the histogram of overall pulse widths for the 24 MSPs. Compared with previous results (blue region), the overall widths increase significantly. For the 19
MSPs that are in our sample and also in Yan et al. (2011b), 15 of them show overall width increase, and on average increases by \( \sim 22 \) per cent. For the 4 MSPs, whose overall width decreases, the decrease is small and could be because of the uncertainty of measurements. In Fig. 26, the W10 and W50 are plotted against frequency for each MSP. We see no strong evidence that the pulse width decreases as the frequency increases.
5 FLUX DENSITIES AND SPECTRAL INDICES

5.1 Average spectral index

In Table 4, we present the flux densities and spectral indices for all the MSPs in our sample. Firstly, the unweighted mean flux density $S = \langle I \rangle$ at different frequencies and their uncertainties are given (using methods described in Toscano et al. 1998). Then, the root mean square (rms) fluctuation in individual-observation flux densities are presented. We fit for the spectral index, using a power-law of the form $S = S_0 \nu^\alpha$, and present the spectral indices in the last column. In Fig. 27 the flux densities are plotted against frequency for each

Figure 23. Multi-frequency polarization profiles for PSR J2145–0750. See Fig. 1 for further details.
MSPs, and the best fitted power-law spectra are indicated with red dashed lines.

Compared with Yan et al. (2011b), the mean flux densities of several MSPs (e.g., PSR J0711−6830) in the 20cm band show significant differences, which is caused by interstellar scintillation effects. Although we are averaging over a much longer time-span and a larger number of observations, we find that measurements of flux densities are still biased by diffractive scintillations as the distributions of flux density for a given pulsar are clearly non-gaussian.

From Fig. 27, we can see that a single power-law can fit the spectra of most MSPs. Exceptions are PSRs J1600−3053 and J1713+0747, whose spectra show flattening at lower frequencies. The spectral indices are consistent with results...
Table 3. Pulse width for PPT A MSPs.

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Figure 25. The overall pulse width for 19 PPTA MSPs included in both Yan et al. (2011b) and our sample. Blue histograms show the results of Yan et al. (2011b). Red histograms show the results of our data sets.

Presented in Toscano et al. (1998) within the measurement uncertainties, but have much smaller uncertainties because of our improved measurements of flux densities. However, compared with Kramer et al. (1999a), the spectral indices show differences clearly larger than the uncertainties. Such discrepancies could be caused by the flux density measurements being biased by scintillation effects, and also the narrower frequency range we are using. We derive a mean spectral index of $-1.8 \pm 0.1$, which is consistent with previous results and support the idea that MSPs and normal pulsars have similar emission characteristics.

5.2 Phase-resolved spectral index

The bottom part of the left-side panel of Fig. 24 shows the phase-resolved spectral index for each MSP. The mean pulse profiles of three observing bands are aligned as described in Section 2.3. All mean pulse profiles are rebinned into 128 phase bins and the spectral index is fitted for each bin whose signal exceeds three times of the baseline rms noise. The red dashed line represents the average spectral index with its uncertainty indicated by the yellow region.

We see that the phase-resolved spectral indices show similar components as the mean pulse profiles. Different components of the profile often have different spectral indices. The spectral indices at different pulse phase could be quite different, and also deviate from the average spectral index. For some MSPs, some part of their spectral indices have larger uncertainties, which indicates that their spectra can not be well fitted with a simple power-law. One exam-
Figure 26. Pulse widths at 10 and 50 per cent of the peak flux density, both in degrees of longitude. Red and blue points represent W10 and W50, respectively.

6 POLARIZATION

6.1 Average polarization parameters

In Table 5, the fractional linear polarization $\langle L \rangle / S$, the fractional net circular polarization $\langle V \rangle / S$ and the fractional absolute circular polarization $\langle |V| \rangle / S$ at different frequencies are presented. All the polarization parameters are calculated from the average polarization profiles we present in Section 3. The means are taken across the pulse profile where the total intensity exceeds three times of the baseline rms noise.

We find no clear evidence that the fractional linear polarization shows simple frequency evolution for MSPs in our sample, and so does the fractional circular polarization and fractional net circular polarization. This is also no evidence that sources that are highly polarized depolarize rapidly as reported previously [Kramer et al. 1999a].

6.2 Phase-resolved fractional linear polarization

The bottom part of the right-side panel of Fig. 24 shows the phase-resolved fractional linear polarization for each MSP. Same as calculating the phase-resolved spectral index, the mean pulse profiles are aligned and rebinned into 128 phase bins. Then at each frequency, the fractional linear polarization is calculated for each bin whose linear polarization exceeds three times of its baseline rms noise. The red dashed line represents the average fractional linear polarization.

For most MSPs, the phase-resolved fractional linear polarization shows good correlation across bands. However, we...
also find that for some MSPs, the fractional linear polarization of certain component changes a lot at different frequencies. There are evidences that the orthogonal and non-orthogonal mode transitions appear when the linear polarization are weak. We find that pre-cursors and post-cursors seem to have higher fractional linear polarization. Such features can be observed in pulsars such as J1603−7202, J1939+2134, J2145−0750, J2241−5236. However, for PSR J1744−1134, we do not see high fractional linear polarizations in the pre-cursors.

### 7 DISCUSSION AND CONCLUSION

- General discussion of frequency evolution of pulse profile.
- Indications of phase-resolved spectral index and fractional linear polarization.
- Radiation mechanism.
- Beaming.
- MSPs and normal pulsars.
- ...

### REFERENCES

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Johnston S. et al., 1993, Nature, 361, 613
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Figure 27. Flux density spectra for 24 MSPs. The fitted power-law spectra are indicated with red dashed lines.
Table 5. Polarization parameters for PPTA MSPs.

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