Simultaneous 50 cm/10 cm single-pulse polarization observations of PSR J0953+0755

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Abstract We report on simultaneous single-pulse observations of PSR J0953+0755 at 732 and 3100 MHz made using the Parkes 64-m radio telescope at two epochs. Another non-simultaneous 1369 MHz observation has also been analyzed to compare polarization properties of this pulsar at different frequencies. The previously reported low-level bridge emission between the interpulse and the main pulse is notably present at 732 MHz. However, the bridge emission becomes very weak or undetectable at higher frequencies. The cross-correlation analysis of simultaneous observations indicates that the total intensity of single pulses is highly correlated, which implies a same emission mechanism responsible for the two frequencies. We confirm that the abrupt PA jumps are non-orthogonal in this pulsar which probably result from the overlapping emission from two non-orthogonal polarization modes and the separation between different polarization modes is frequency-dependent. At all three frequencies, the dominant modes are clearly associated with negative values of circular polarization, but the association seems unclear for weak modes.

Key words: stars: neutron — pulsars: general — pulsars: individual (PSR J0953+0755)

1 INTRODUCTION

Although the first pulsars were discovered more than 50 years ago, there is still no consensus on the detailed physics of the emission process in the pulsar magnetosphere. Soon after their discovery, it was quickly realized that the radio emission of pulsars is highly polarized (Lyne & Smith 1968). Many pulsars show an “S” or “inverse S” shape in the linear polarization position angle (PA) variation curves (e.g., Weisberg et al. 2004), which can be approximately described by the ‘rotating vector model’ (RVM, Radhakrishnan & Cooke 1968). However, not all pulsars exhibit such smooth and continuous PA variations with pulse phase. For example, many millisecond pulsars show very flat or disturbed PA variations (e.g., Yan et al. 2011). Abrupt PA jumps of approximately 90° are often observed (e.g., Manchester et al. 1975; Han et al. 2009). Such discontinuities are explained using the superposition of two orthogonal polarization modes
(OPMs) in the radiation (e.g., McKinnon & Stinebring 1998). The OPMs may arise from the radiation of positrons and electrons that are moving along the curved magnetic field lines, which is orthogonally polarized (Gangadhara 1997), or from the strong refraction effects that occur in the pulsar magnetosphere (Petrova 2001). Non-orthogonal PA jumps has also been observed in some pulsars (Backer & Rankin 1980; Stinebring et al. 1984a; McKinnon 2003). The non-orthogonal jumps in PA can be interpreted as resulting from overlapping emission from two non-orthogonal polarization modes (NPMs, McKinnon 2003; Edwards 2004).

Pulsars are broadband pulsating sources and their emission covers a wide range of wavelengths. It is known that radio pulsars show a diverse profile evolution with frequency. Some pulsars have a relatively stable pulse profile morphology over a wide frequency range, while others show remarkable variation in pulse width, separation of profile components and/or profile shape (e.g., Komesaroff 1970; Cordes 1978; Rankin 1983; Hanks & Rickett 1986; Lyne & Manchester 1988; Johnston et al. 2008; Hanks & Rankin 2010). Simultaneous multifrequency studies of pulsar polarimetric radiation properties are of great significance for investigating the puzzling pulsar emission problem, which can lead to a better understanding of pulsar emission mechanisms.

Using the Effelsberg radio telescope, Bartel & Sieber (1978) simultaneously observed single pulses from PSRs B0329+54 and B1133+16 at 327 and 2695 MHz, and they found evidence for a broadband nature of the emission. Simultaneous single-pulse observations were conducted for some pulsars using the Pushchino BSA transit array at 102.5 MHz and the Effelsberg radio telescope at 1720/1700 MHz (Bartel et al. 1981; Kardashev et al. 1986). It was shown that pulse nulling occurred simultaneously at both frequencies for PSR B0809+74. Davies et al. (1984) simultaneously observed PSR B0809+74 using the Pushchino BSA transit array at 102 MHz and the Jodrell Bank telescope at 406 and 1412 MHz and their analysis showed that nulls at 406 MHz always corresponded to nulls at 102 MHz, but not vice versa. Simultaneous observations of giant pulses of the Crab pulsar between the VLA at 1.4 GHz and the Green Bank 25-m telescope at 0.6 GHz were conducted by Salmen et al. (1999). It was found that about 70% of the giant pulses are detected at both 1.4 and 0.6 GHz, implying a broadband emission mechanism. Karastergiou et al. (2001) presented simultaneous observations of PSR B0329+54 at 1.4 and 2.7 GHz using the Jodrell Bank and Effelsberg radio telescopes respectively, and they reported that the pulses at different frequencies are highly correlated in their total intensity. To investigate OPMs in PSR B1133+16, Karastergiou et al. (2002) used the Effelsberg telescope at 4.85 GHz and the Lovell telescope at 1.41 GHz to simultaneously observe this pulsar. Their results showed that there is a high degree of correlation between the polarization modes at the two frequencies. Karastergiou et al. (2003) investigated circular polarization in pulsar radio emission through simultaneous observations of PSR B1133+16 using the Effelsberg telescope at 4.85 GHz and the Jodrell Bank telescope at 1.41 GHz. They found significant association of the handedness of circular polarization with the OPM phenomenon at two different frequencies for PSR B1133+16. Kramer et al. (2003) presented a study of flux density measurements of single pulses simultaneously observed at four different frequencies for PSRs B0329+54 and B1133+16. The intrinsic pulse-to-pulse modulation indices were derived which show a minimum around 1 GHz. Bhat et al. (2007) analyzed the phenomenon of pulse nulling using single-pulse data of PSR B1133+16 from simultaneous observations at four frequencies. They found that nulling does not always occur simultaneously at all four frequencies of observation.

PSR J0953+0755 is an early discovered bright pulsar (Pilkington et al. 1968). Due to its relatively large flux density, this pulsar has been extensively studied in terms of average profile and single-pulse properties. PSR J0953+0755 is the first pulsar in which an interpulse was discovered (Rickett & Lyne 1968). Hanks & Cordes (1981) detected a low-level bridge of emission that connects the interpulse and the main pulse. Abrupt PA jumps had been observed in PSR J0953+0755 at several different frequencies (Backer & Rankin 1984; Stinebring et al. 1984a; Stinebring et al. 1984b; Smits et al. 2006). In this paper, we report on simultaneous single-pulse polarization observations for PSR J0953+0755 at 732 and 3100 MHz as well as a
Table 1: Summary of the observations. Note that the symbols $\tau_{\text{samp}}$ and $T_{\text{obs}}$ represent the sampling interval and the duration of the observation, respectively.

<table>
<thead>
<tr>
<th>Date (yyyy-mm-dd)</th>
<th>MJD</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>$\tau_{\text{samp}}$ (µs)</th>
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non-simultaneous 1369 MHz observation. Section 2 describes details of the observations and data processing. The results are given in Section 3. We summarize and discuss our results in Section 4.

2 OBSERVATIONS

The observational data were downloaded from the Parkes Pulsar Data Archive, which were obtained with the Parkes 64-m radio telescope. Simultaneous 732 MHz and 3100 MHz observations were made on 2014 October 19 (MJD 56949) and 2014 November 7 (MJD 56968), using the dual-band 10/50 cm receiver and the Parkes digital filterbank systems PDFB3 and PDFB4. The non-simultaneous 1369 MHz (20 cm) observation was made on 2016 March 5, using the H-OH receiver and PDFB4. See Manchester et al. (2013) for more detailed information on the receiver and backend systems. The observing bandwidths, 64 MHz, 256 MHz and 1024 MHz for 50 cm, 20 cm and 10 cm, respectively, were each divided into 512 channels. The data were sampled every 256 µs for each observation. Details of the observations are listed in Table 1.

The data were dedispersed incoherently using the DSPSR package (van Straten & Bailes 2011) and folded to form single-pulse integrations with the ephemeris from the ATNF Pulsar Catalogue V1.6. The single-pulse integrations were then saved in PSRFITS data format with 512 phase bins per rotation period. The PAZ and Pazi plugins in the PSRCHIVE package were used to remove band edges (5 per cent on each side) and strong narrow-band radio-frequency interference (RFI) and broad-band impulsive RFI in the data. Then the RFI-excised data were then processed using the PSRCHIVE packages. Following Yan et al. (2011), we used the PSRCHIVE program PAC to perform polarization calibration. The rotation measure value $\mathrm{RM} = -0.86 \, \text{rad/m}^2$ was obtained from Johnston & Kerr (2018).

3 RESULTS

3.1 Bridge emission

The low-level bridge emission that connects the interpulse and the main pulse of PSR J0953+0755 was first reported by Hankins & Cordes (1981) at 430 MHz. Bilous et al. (2022) carried out a non-simultaneous dual-frequency single-pulse study for PSR J0953+0755 at 55 MHz and 1.4 GHz, and they concluded that the bridge emission is relatively stronger at lower frequencies. We present polarization profiles for PSR J0953+0755 at 732, 1369 and 3100 MHz in Fig. 1. The green horizontal lines in the expanded plots in the middle row represent three

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1. [https://data.csiro.au](https://data.csiro.au)
4. [https://psrchive.sourceforge.net/](https://psrchive.sourceforge.net/)

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times the baseline noise rms level. From Fig. 1 we can see that the 732 MHz profile shows a clear connecting bridge of emission between the interpulse and the main pulse, which significantly exceeds the three times level of the baseline noise. However, such a bridge of emission becomes invisible in profiles at the two higher frequencies. This is in good agreement with the results of Bilous et al. (2022).

3.2 Cross-correlation analysis

In order to investigate the correlation between pulse energy variations of individual pulses at 732 and 3100 MHz, we plotted pulse energy variations for pulse sequences of the 2014-10-19 simultaneous observations in Fig. 2. To reduce the effect of the baseline noise, the pulse energy was estimated for each individual pulse by summing the intensities of the pulse phase bins within the longitude range determined by the 10% level of pulse peak. In the upper two panels of Fig. 2, long time-scale energy variations between the two frequencies are caused by interstellar scintillation. A very good correlation can be clearly seen in the lower two panels.

To quantitatively describe the correlation between pulse energy variations of individual pulses at 732 and 3100 MHz, we calculated the cross-correlation function (CCF) for them which is shown in Fig. 3. As is shown in Fig. 3, the CCF reaches a maximum value of 0.928 at zero lag, which means a very strong correlation between pulse energy variations of pulse sequences at 732 and 3100 MHz. The synchronous variations of pulse energy between 732 and 3100 MHz imply that they are the intrinsic emission variability of this pulsar.

In order to further study the bin-by-bin correlation between the simultaneous observations, following Popov (1986) and Karastergiou et al. (2001), we carry out a cross-correlation analysis of the intensity fluctuations of single pulses at different phase bins. In this method, for two single-pulse sequences simultaneously observed at two frequencies, each with $n$ pulses, the
two-dimensional correlation array $c_{i,j}$ is given by:

$$c_{i,j} = \frac{1}{n \cdot \sigma_{f,i} \cdot \sigma_{g,j}} \sum_{k=1}^{n} [f_i(k) \cdot g_j(k) - \langle f_i \rangle \langle g_j \rangle],$$

(1)

where $f_i(k)$ is flux density time series of bin $i$ at one frequency and $g_j(k)$ is the flux density time series of bin $j$ at the other frequency with $k$ being the pulse number, $\sigma_{f,i}$ and $\sigma_{g,j}$ are the standard deviations of the time series $f_i(k)$ and $g_j(k)$, respectively. For each point $(i, j)$, $c_{i,j}$ is the correlation coefficient between the time series $f_i(k)$ and $g_j(k)$. After this analysis, the correlation of the intensity variations between different phase bins of the simultaneous observations becomes visible. Figures 4, 5 and 6 show the contour map of distribution of the correlation coefficient for total intensity $I$, linear polarized intensity $L$ and circular polarized intensity $V$, respectively. Each map is an average picture obtained from 14249 pulse at each frequency.

As the red dashed diagonal line represents the same phase bins between the two frequencies, it is not surprising that large correlation coefficients of total intensity are mainly distributed along the diagonal line in Fig. 4. The correlation maxima are located within the longitude range of $250^\circ - 260^\circ$, which corresponds to the trailing edge of the pulse profile. The correlation maxima exceed 0.8 and this means that the trailing edges of pulse profiles at 732 and 3100 MHz are highly correlated with each other in total intensity. In Fig. 5, the correlation maxima of linear polarization are also located within the longitude range of $250^\circ - 260^\circ$ which corresponds to the main components of linear polarization. However, the correlation maxima of linear polarization are only about 0.5. In circular polarization (Fig. 6), although the two frequencies are almost uncorrelated (with correlation maxima of less than 0.15), the most correlated region ($255^\circ - 260^\circ$) is consist with total intensity and linear polarization.
Fig. 3: The normalized cross-correlation between the pulse energies of pulse sequences of PSR J0953+0755 at 732 and 3100 MHz.

3.3 PA jumps

Orthogonal and non-orthogonal PA jumps had been reported in PSR J0953+0755 at different radio frequencies by earlier investigators (Backer & Rankin 1980; Stinebring et al. 1984a; Stinebring et al. 1984b; Smits et al. 2006). In this section, we investigate whether the observed PA jumps in our data at three frequencies are 90° or not.

Fig. 7 shows the PA distribution as a function of pulse phase at both 732 and 3100 MHz. Together with the linear polarization, the average pulse profiles at both frequencies are also presented in Fig. 7. Similarly, we plot the PA distribution, the integrated pulse profile and the linear polarization at 1369 MHz in Fig. 8. It can be seen that the PA distributions at both 732 and 1369 MHz show jumps between two modes in two regions, while there is only one region showing PA jumps at 3100 MHz. The PA jumps in region I had also been detected in earlier studies. Backer & Rankin (1980) reported that the mode separations are non-orthogonal, which are 65°–70° for region I at 430 MHz. Stinebring et al. (1984a) and Stinebring et al. (1984b) reported that, at 1404 and 800 MHz, the mode separations near the main pulse peak are close to 90°. However, they did not give exact values of the separations.

To calculate the separation between two different PA modes, we first obtained the PA for each phase bin of every pulse whose flux density of the linear polarization exceeds three times the baseline noise level. Fig. 9 presents an example of a phase bin in region I that shows well separated PA modes at both 732 and 3100 MHz. The PA histograms at the two frequencies in Fig. 9 can be fitted by the combination of two Gaussian functions. The best fitted Gaussian means are $\mu_1 = -42.0°$, $\mu_2 = 29.5°$ for 732 MHz and $\mu_1 = -11.5°$, $\mu_2 = -99.9°$ for 3100 MHz. Thus, for bin 371, the mode separations are 71.5° and 88.4° at, respectively, 732 and 3100 MHz. It is worth mentioning that the two modes at some phase bins cannot be well separated as we can
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Fig. 4: Correlation map of pulse-to-pulse total intensity fluctuations at different longitudes for simultaneous 732 and 3100 MHz observations. The total intensity fluctuations of each phase bin of one observation are correlated against each bin of the other observation. The normalized pulse profiles for total intensity of PSR J0953+0755 at 732 and 3100 MHz are plotted on the left and bottom side panels, respectively. The red dashed diagonal line represents the same phase bins between the two frequencies.

As mentioned above, PA jumps were also observed in a second region (region II in Figures 7 and 8) in our 732 and 1369 MHz data, which had not been reported in the literature. Following the analysis of region I, we obtained the average mode separation calculated from phase bins in region II for both frequencies. The derived 732 MHz separation is 67.5°, while the 1369 MHz separation is 85.1°. Our results at three frequencies imply that the PA jumps observed in PSR J0953+0755 are NPMs, rather than OPMs proposed by some earlier investigators.
3.4 The $V$-NPM correlation

The connection between the sign of circular polarization $V$ and the PA value was first noted by Cordes et al. (1978). They found that negative values of $V$ are associated with one PA mode, and positive values with the other mode in PSR B2020+28. Karastergiou et al. (2003) reported that the $V$-OPM correlation is weaker at the higher frequency for PSR B1133+16. Following Cordes et al. (1978), to investigate this correlation in our data, we plotted $V$ versus PA in the single pulses for a particular phase bin of PSR J0953+0755 where the distribution of PAs is bimodal at three frequencies in Fig. 11. In Fig. 11, the dominant modes (mode A at 732 MHz, mode A at 1369 MHz and mode B at 3100 MHz) are obviously associated with negative values of $V$. However, for the weak modes (mode B at 732 MHz, mode B at 1369 MHz and mode A at 3100 MHz), the association of $V$ with PA is not so clear. We therefore plotted the distribution of $V$ for each mode at three frequencies to look for clues to the association. From Fig. 12, we can see that the dominant modes at three frequencies prefer negative values of $V$, while the
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Fig. 6: Correlation map of pulse-to-pulse circular polarized intensity fluctuations at different longitudes for simultaneous 732 and 3100 MHz observations. The total intensity fluctuations of each phase bin of one observation are correlated against each bin of the other observation. The normalized pulse profiles for circular polarized intensity of PSR J0953+0755 at 732 and 3100 MHz are plotted on the left and bottom side panels, respectively. The red dashed diagonal line represents the same phase bins between the two frequencies.

weak modes do not show dominant sign of V. Our results imply that only the dominant mode in NPMs is clearly associated with the sign of circular polarization V.

4 DISCUSSION AND CONCLUSIONS

In this paper, we studied the single-pulse polarization observations of PSR J0953+0755 with the Parkes 64-m radio telescope at 732, 1369 and 3100 MHz, in which the 732 and 3100 MHz observations were made simultaneously.

Some studies at low radio frequencies reported the detection of giant pulses (GPs), a special kind of narrow (with widths on a time-scale of nanoseconds to microseconds) and very bright pulses, in PSR J0953+0755 (Smirnova 2012; Singal & Vats 2012; Tsai et al. 2016; Kuiack et al. 2020). However, Bell et al. (2016) suggested that the extremely strong pulses observed in PSR J0953+0755 are consistent with diffractive scintillation and are not intrinsic to the pulsar. Bilous et al. (2022) argued that the “GPs” claimed by Kuiack et al. (2020) are not “classical”
Fig. 7: Panels (a) and (c): the total intensity (solid line) and linear polarization (dotted line) profiles of PSR J0953+0755 at two frequencies. Panels (b) and (d): the color-scale PA histograms. The brighter areas in the color-scale histograms correspond to more frequent values of PA. The vertical dashed lines confine the regions (II and I) that show abrupt PA jumps.

GPs due to normalization with a noncontemporary average flux density from the literature. We had also tried to search for GPs in our data at three frequencies. However, after correction for scintillation effects ([Wen et al. 2016]), we failed to find any bright pulses with the energy larger than 10 times the average pulse energy.
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Fig. 8: Similar to Fig. 7, the top panel shows the total intensity (solid line) and linear polarization (dotted line) profiles of PSR J0953+0755 at 1369 MHz. The bottom panel presents the color-scale PA histograms. The vertical dashed lines confine the same regions as Fig. 7 that show abrupt PA jumps.

The natural interpretation of the 180° separation between the interpulse and the main pulse is that the pulsar might have an orthogonal geometry, where the main pulse is radiated above one polar cap and the interpulse above the other (Hankins & Fowler 1986). Another possibility of producing the interpulse is the so-called single-pole model, in which there are two cases (Manchester & Lyne 1977; Lyne & Manchester 1988; Maciesiak et al. 2011). In the first case, emission occurs over a large fraction of the pulse period and the main pulse and the interpulse represent two edges of a very wide emission beam. The second case works for narrow beam pulsars in which the magnetic and rotation axes of the pulsar are close to alignment, meanwhile the line of sight is near the rotation axes too. Of course it is also possible that a pulsar with wide beams showing the interpulse emission is a nearly aligned rotator. The presence of a low-intensity bridge of emission between the interpulse and the main pulse is clear evidence against the orthogonal geometry (i.e., supporting the single-pole model). The bridge emission was detected in PSR J0953+0755 (Hankins & Cordes 1981; Bilous et al. 2022) and the separation between the interpulse and the main pulse is 210°, which suggest that the interpulse and the main pulse probably come from the same magnetic pole for PSR J0953+0755 (Maciesiak et al. 2011; Malofeev et al. 2022). Our results show that the weak bridge of emission is clearly visible for PSR J0953+0755 at 732 MHz, while it becomes undetectable at 1369 and 3100 MHz. This is in good agreement with Bilous et al. (2022) and Malofeev et al. (2022) who found that the bridge emission is stronger at lower frequencies. The frequency dependence of the bridge emission may be common in pulsars with interpulse emission. Then the bridge of emission can be observed in many pulsars with interpulse emission by high-sensitivity observations at low frequencies.

Following Popov (1986) and Karastergiou et al. (2001), we carried out a cross-correlation analysis for PSR J0953+0755, which provides an approach to investigate subpulse intensity variations between different phase bins of the pulse profile. Consistent with the previously
published results of PSR B0329+54 (Karastergiou et al. 2001), the total intensity of PSR J0953+0755 is highly correlated between 732 and 3100 MHz (Fig. 7). There are also differences between PSR B0329+54 and PSR J0953+0755. For PSR B0329+54, the correlation maxima correspond to pulse peaks of the profile. But for PSR J0953+0755, the most correlated region is the trailing edge of the main pulse. The good total intensity correlation means that a single radiation process in the pulsar magnetosphere is responsible for the emission variations at the two frequencies for PSR J0953+0755. The two-dimensional correlation array shows that the linear and circular polarization intensities are less correlated. Perhaps it is because the linear and circular polarized intensities are relatively weak.

The abrupt PA jumps of PSR J0953+0755 had been taken as OPMs by some investigators. By calculating mode separation for bins within the PA jumping regions at three frequencies for PSR J0953+0755, we found that the PA mode separation is 71°, 86.3° and 82° at, respectively, 732, 1369 and 3100 MHz for region I in Fig. 7. We also obtained the mode separation for region region II, which is 67.5° and 85.1° at, respectively, 732 and 1369 MHz. We therefore
Fig. 10: The PA distribution for phase bin 371 at 1369 MHz. The red dotted line is the fitting for the distribution based on the combination of two Gaussian components. The fitted means of the two Gaussian components are $-38.4^\circ$ and $49.7^\circ$, respectively.

Fig. 11: Scatter plot of the circular polarization $V$ versus PA for bin 371 that shows clear PA jumps between two polarization modes at three frequencies. The horizontal dashed lines correspond to $V = 0$.

Conclude that the PA jumps observed in PSR J0953+0755 result from NPMs and the observed mode separations are frequency dependent. Petrova (2006) proposed that OPMs can become NPMs due to polarization transfer as the radio wave propagates through pulsar magnetosphere. Karastergiou (2009) suggested interstellar scattering as an alternative explanation to the generation of NPMs.

Cordes et al. (1978) reported a very good correlation between the sign of circular polarization $V$ and the PA values for phase bins where the distribution of PAs is bimodal in PSR B2020+28, where negative values of $V$ are associated with one PA mode, and positive values with the other mode. Consistent with Karastergiou et al. (2003) who argued that circular po-
polarization is not perfectly associated to the dominant polarization mode in PSR B1133+16, we found that only the dominant mode prefers negative values of $V$, but the weak mode seems not to be associated with circular polarization in PSR J0953+0755. High-sensitivity observations using large radio telescopes such as FAST could figure out the correlation between circular polarization and the weak polarization mode.

Multifrequency observations can help reveal the complicated frequency dependence of pulsar emission behaviours, such as the weak bridge emission between the interpulse and the main pulse and the polarization mode separations of NPMs presented in this paper. More investigation of possible emission models is needed to clarify the mechanism(s) responsible for such observed phenomena.

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