ASTRONOMY

Are there real orthogonal polarization modes in pulsar radio emission?

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Abstract The orthogonal polarization modes (OPM) have been reported observationally and widely accepted by pulsar researchers. However, no acceptable theory can explain the origin of the OPM, which becomes a mystery in pulsar research field. Here a possible way to solve this mystery is presented. We ask a question: Does there exist any real so-called OPM in pulsar radiation? It is proposed that the 'observed OPM' in individual pulses could be the results of depolarization of pulsar radiation and the observational uncertainties originated from polarimeter in observation. A possible method to check this idea is suggested. If the idea is verified, the pulsar research would be influenced significantly in theory and in observation.

Keywords: pulsars, polarization, radiation mechanisms.

Pulsars are effective astrophysical laboratories for quantum theory and gravitation theory. However, how to reproduce the observed radiation theoretically is still one of the most essential challenges in pulsar study. It is well known that the polarization observations are very important for providing much information about pulsar physics, but there are still many troubles in explaining the polarization data.

One of the difficulties in understanding pulsar polarization observations is the polarization position angle jumps in mean (or integrated) pulses as well as in individual pulses[1—3]. For mean pulses, it is generally found that position angles would have discontinuities about 90° at some longitudes where the linear polarization intensities are near zero (totally depolarized). For individual pulses, the position angles would be dispersed or have two ~ 90° separated distributions at some observational longitude bins where the linear polarization percentages are remarkably small. A famous example to display the polarization position angle jumps in individual pulses is shown in fig. 1 for PSR B2020 + 28[1]. In case 'A' and 'C', the two position angle distributions are clear, and the linear polarization percentages are obviously low. In case 'B', there is only one position angle distribution, and the emission in each longitude point is highly linearly polarized. It means that such orthogonally distributed position angles are usually observed only in the part of the profiles where the linear polarization is low[4]. A conclusion from the observation is that, both for mean profiles and for individual pulses, the position angle jumps are related to low linear polarization (percentage) at all time.

Based on the above observational facts, there should be two possibilities logically: one is

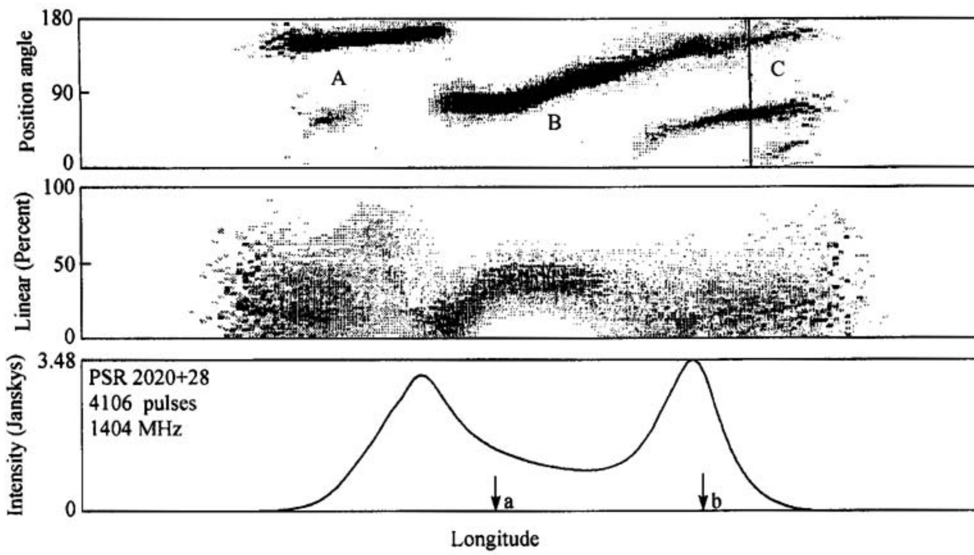

Fig. 1. Polarization distribution of PSR B202 + 28. The top plot shows the position angle distribution; the middle plot shows the linear polarization percentage of individual pulses; the lowest plot gives the integral pulse profile. The observation is done by Stinebring et al.[1].

that 'position angle jump' causes 'low linear polarization', the other is that 'low linear polarization' causes 'position angle jump'. Many authors believe, without justification, that the position angle jumps should be attributed to the appearance of OPM[1—3], in-coherent superposition of the OPM is the origin of depolarization. However, why is another possibility impossible? We investigate this possibility in this paper.

Previously, Stinebring et al.[1] concluded that most of pulsar emission occurs in one orthogonal mode or the other, which is called orthogonal polarization modes (OPM). At a given longitude, the plane of polarization can be of two perpendicular or nearly perpendicular states. Which one can operate was governed by some variability as yet not understood. The OPM can explain many things: the sharp jumps of position angles, the depolarization of linear as well as circular polarization due to the existence of both modes at the same time[2]. However, there is no acceptable theory to produce such orthogonal modes, which is called 'OPM problem'.

For mean pulses, it is suggested that the depolarization and position angle jumps might be attributed to the relative longitude shifts of pulsar beams[5,6]. Such kind of longitude shifts of pulsar beams is natural in the inverse Compton scattering (ICS) model[7]. For individual pulses, many authors believe that there are two orthogonal modes at a given longitude. Nevertheless, there may be in fact two possibilities to produce such orthogonal modes. One is that the emission for a given frequency is emitted at different heights, and the other is that there is an unknown emission mechanism to produce orthogonal modes at a same emission point[8]. The first possibility has been studied already[6,7]. But for the second one, no acceptable theory has been found to produce such orthogonal modes hitherto known. Thus, the 'OPM problem' still confuses the pulsar world.

We ask a question here: Are really such 'orthogonal modes' the reason for the 'low linear polarization'? Otherwise, might the 'low linear polarization' be responsible for the observed 'orthogonal modes'? Many authors believe that the reduction in the percentage of linear polarization is caused by in-coherent superposition of the OPM. Contrary to the above idea, another possibility (i.e. the 'low linear polarization' is the reason for producing the observed 'position angle jumps') is suggested in this paper. Our analysis and simulations show that, when the linear polarization percentages are low enough, the position angles would be distributed in two areas separated nearly ninety degrees. A suggestion to check this idea is presented.

We show how 'low linear polarization' causes the so-called 'position angle jumps' in mean-pulses and in single-pulses in secs. 1 and 2, respectively. Some troubles faced by OPM radiation mechanism are summed up in sec. 3. Finally, conclusion and discussion are given in sec. 4.

1 Position angle jumps in mean pulses: depolarization?

Almost certainly, for observed mean-pulses, the smoothly changing position angle curves will suddenly jump at some longitudes, where the linear polarization is highly depolarized. These facts can be understood under the properties of Stokes parameters. It could be verified mathematically that the position angle would jump 90° when the line of sight travels across a singular point[5, 6], where the linear polarization intensity is zero.

The four Stokes parameters $\{I, Q, U, V\}$, from which one can obtain linear polarization intensity $L = \sqrt{Q^2 + U^2}$ and position angle χ (see eq. (1) below), are functions of observational longitude ϕ. For the sake of simplicity, we let $V = 0$, as the linear polarization is focused on here. At a singular point ($\phi = \phi_s$), $L = 0$ means $Q(\phi_s) = 0$, $U(\phi_s) = 0$. Expanding Q and U near singular point,

$$Q(\phi_s + \Delta) = \frac{\partial Q}{\partial \phi}\Delta + \frac{1}{2}\frac{\partial^2 Q}{\partial \phi^2}\Delta^2 + \frac{1}{3!}\frac{\partial^3 Q}{\partial \phi^3}\Delta^3 + \cdots,$$

$$U(\phi_s + \Delta) = \frac{\partial U}{\partial \phi}\Delta + \frac{1}{2}\frac{\partial^2 U}{\partial \phi^2}\Delta^2 + \frac{1}{3!}\frac{\partial^3 U}{\partial \phi^3}\Delta^3 + \cdots.$$

Assuming $\frac{1}{q!}\frac{\partial^q U}{\partial \phi^q}\Delta^q$ and $\frac{1}{u!}\frac{\partial^u U}{\partial \phi^u}\Delta^u$ are the lowest non-zero power terms of Q and U, respectively, and $\nu = \min[q, u]$, one could find that $\chi(\phi_s + \Delta) - \chi(\phi_s - \Delta)$ should be $\pm 90°$ as long as ν is an odd number[1)]. It is very possible that $\nu = 1$, thus, position angle naturally jumps 90° if $L = 0$[6]. Therefore, the reason that position angle jumps in integrated profiles might be why the beamed radiation is depolarized. Depolarization should be the cause of position angle jumps in mean-pulses.

There are many ways to cause depolarization. First of all, depolarization may have an intrinsic origin. As emission beams are formed in different heights, and each of them has different position angle, depolarization must take place by incoherent superposition of such emission beams. In the ICS model[7], different emission beams are formed in different heights, hence, the retardation and aberration effects could make the apparent emission beams be superposed incoherently[5,6]. Secondly, depolarization might be originated from propagation process, such as the scattering by interstellar medium or magnetospheric plasma[4], and the propagating properties of different radiation modes in plasma. The third way might be the result of observational effect. Since

1) One might easily obtain this conclusion by inspecting the position angles in Q-U plane (two-dimension Poincare sphere for $V = 0$).

the Stokes parameters are added from many frequency channels after de-dispersion, the emissions in each frequency channel are incoherently superposed. Such kind of treatment in observation should also depolarize the original radiation.

2 Position angle jumps in single-pulses: observational uncertainty?

There are many factors to reduce the precision of observational results, such as noises from the observational system and the sky background. Usually, we put thresholds for the total intensity (I) and the linear polarization intensity (L) in each longitude bin in order to exclude fake polarization due to the observational error. For example, we select observational data whose I and L are greater than 5 to 10 times of off-pulse rms. However, as will be discussed in this section, some fake polarization data, which may be responsible for the observed 'position angle jumps' in individual pulses[5], do survive from such selection.

Some observational uncertainties can cause the observed position angles to 'jump' in individual pulses, such as the 'error transference' (sec. 2.1), the unequal rms of Stokes parameter Q and U (sec. 2.2), and the fake linear polarization (sec. 2.3). All these uncertainties can bring wrong polarization information.

2.1 Position angle 'jumps' in individual pulses due to the error transference

If x is a random number, then the function $y = f(x)$ is also random. The random distribution of y is known as long as the distribution of x is given. For example, let the distribution function of x be a gaussian distribution, with the expectation value x_0. The distribution function of y should be dependent on the function $f(x)$. If $f(x)$ is a monotonous function near x_0, the distribution function of y is approximately a gaussian. Whereas, if $f(x)$ is a very complex function near x_0, the distribution function of y is also complicated.

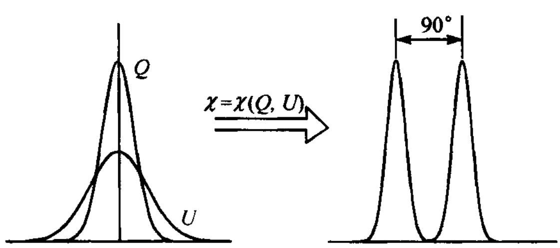

Fig. 2. A sketch picture for the possibility of the linear polarization position angle 'jump' due to the error transferring from Q and U.

It is known that the position angle χ is a function of the Stokes parameters Q and U[1)]

$$\chi = \frac{1}{2}\left[\operatorname{sign}U\cos^{-1}\frac{Q}{L} + \pi(1 - \operatorname{sign}U)\right], \tag{1}$$

which is 'singular' (unusual) near $L = \sqrt{Q^2 + U^2} = 0$. Here $\operatorname{sign}U = +1$ ($\operatorname{sign}U = -1$) if $\operatorname{sign}U > 0$ ($\operatorname{sign}U < 0$.). This property of singularity of χ would cause two error distribution peaks (see fig. 2), which will be discussed later in sec. 2.2. In a word, the observational uncertainty (error) of Q and U could bring an error distribution of χ in two regions with 90° separation by the error transference effect. Such observational results might be mistakenly considered as position angle 'jumps' in a real beamed radiation.

1) Usually $\chi = \frac{1}{2}\tan^{-1}\frac{U}{Q}$, depending on the signs of Q and U. From $\begin{cases}\sin 2\chi = U/L \\ \cos 2\chi = Q/L,\end{cases}$ one can get a general expression for χ, where the value region of χ is from 0° to 180°.

2.2 Position angle jumps due to unequal errors of Q and U

Usually, the rms of the Stokes parameter Q and that of U are not equal for an astronomical polarimetry, i.e. $\sigma_Q \neq \sigma_U$. The difference between σ_Q and σ_U can be as large as several percentages in Yobservations. The observed linear polarization position angles could 'jump' during different observing time as long as $\sigma_Q \neq \sigma_U$. As demonstrated in fig. 3, we see that $\chi_B - \chi_A$ is about 0°, and $\chi_B - \chi_C$ is about 90°.

The reason for $\sigma_Q \neq \sigma_U$ might be diversity. For example, for some polarimetry, the Stokes parameters $Q = S_0 - S_{90}$ and $U = S_{45} - S_{135}$ are computed from the hybrid networks' out-put signals. Here S_0 and S_{90} are the observed intensity from two orthogonal dipole antenna, S_{45} and S_{135} are the intensity received from a system which has been rotated 45 degrees. For a dipole antenna, S_0 and S_{90} are obtained directly. However, the S_{45} and S_{135} are yielded through a turnstile junction where the phase misalignment can make the rms of S_{45}(and S_{135}) larger than the rms of S_0(and S_{90}). So, the rms of Q and that of U cannot be equal because of the imperfection of the turnstile junction.

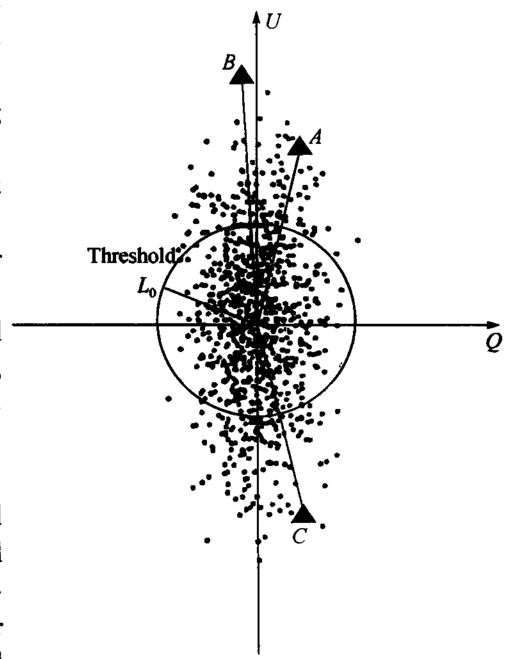

Fig. 3. A demonstration of position angle 'jumps' which come from observational uncertainty. Position angles χ_A, χ_B and χ_C are for points A, B, and C, respectively.

Simulations of this kind of polarimetry are given in fig. 4, from which we see that

(i) The observed percentages of polarization Π' are much greater than the true percentage Π, if Π is small enough. Observed linear polarization may be larger than that of the true value.

(ii) The position angle 'jumps' take place when linear polarization percentage $\Pi_l \leqslant 0.1\%$. When $\Pi_l \geqslant 1\%$, there are few possibilities to make position angle jump.

Because the observational uncertainty is of random, position angle jumps that come of this kind of errors discussed above can be avoided by more time observation. It is almost impossible that position angle jump due to observational uncertainty appears in integrated profiles.

2.3 The observational noise responsible for fake polarization

For a telescope with an effective detection area A, a frequency bandwidth $\delta\nu$, a time constant τ, and a systematical noise temperature T_{sys}, the systematical noise flux S_{sys} is $S_{sys} = kT_{sys}/A$, where $k = 1.38 \times 10^{-23}\mathrm{J \cdot K^{-1}}$ is the Boltzmann's constant, and the off-pulse rms σ_{off} is

$$\sigma_{off} = \frac{S_{sys}}{\sqrt{\delta\nu\tau}}.$$

Whereas there is a signal with intensity flux S_i, the rms of the signal flux is σ_{on}(the on-pulse rms)

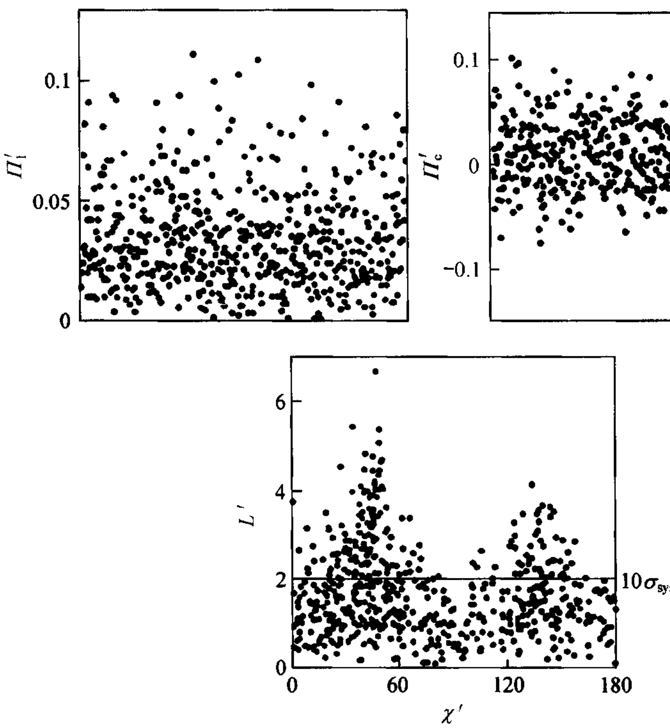

Fig. 4. The simulated scatter plots of the observed polarization degrees of linear polarization Π'_l, and circular polarization Π'_c. The lower one is the $L' - \chi'$ (linear polarization intensity vs. the position angle) plot, where the solid horizontal line shows a possible threshold level for linear polarization. The parameters in the simulation are given in the text.

$$\sigma_{on} = \frac{S_{sys} + S_i}{\sqrt{\delta\nu\tau}},$$

where S_i can be one of the out-put signals from the hybrid networks, such as S_0, S_{90}, S_{45}, S_{135}, S_R, S_L, which are correspondent to the linearly polarized components of the input signals at position angles 0°, 90°, 45°, and 135°, and to the right-hand and left-hand circularly polarized components.

Because $S_i = (S_{sys} + S_i) - S_{sys}$, the rms of S_i is $\sigma_i = \sqrt{\sigma_{off}^2 + \sigma_{on}^2}$. If we assume that S_{sys} is accurate enough (i.e. we have enough time to measure S_{sys}), then $\sigma_i \approx \sigma_{on}$, which will be used in the following discussion.

If we let $A = 40^2\pi$ square meters, $\delta\nu = 10$ MHz, $\tau = 0.3$ ms, and $T_{sys} = 40$ K, then σ_{off} is about 0.2 Jy. For $S_i = 30$ Jy[9], then $\sigma_i = 0.8$ Jy which is more than three times that of σ_{off}, and the fake linear polarization percentage could be as large as 3%. Thus, some data, whose linear polarization is originated from such uncertainty, can also exceed the observational threshold level with an un-negligible possibility.

3 Are real orthogonal polarization modes in pulsar radiation?

We might be in a dilemma if there are really the so-called orthogonal polarization modes in pulsars' beams. First, how is the OPM radiative mechanism produced? No reasonable one has appeared in literature. Furthermore, the two orthogonal modes should be incoherent, which makes the OPM more difficult to be set up. The suggestion for observed 'orthogonal modes' in mean-pulses by Xu et al.[6] is not the real one. In their calculations, two components are emitted in-coherently from different regions. If the two modes are coherent, the total radiation is elliptically polarized, thus no position angle 'jump' appears.

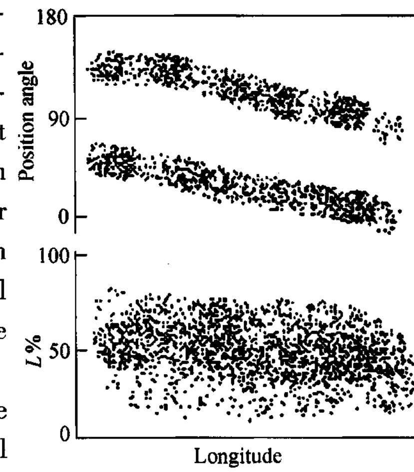

Fig. 5. A possible observational result predicted by OPM models. In the figure, the lowest points present the linear polarization percentages of individual pulses; the upper two distributions are for the position angles.

Secondly, why haven't we seen that single-pulses are highly polarized, but the position angle distribution is till separated by 90° (like fig. 5)? Individual pulses, which could be highly polarized, are generally conjectured to be from single radiation elements. Since two orthogonal modes are incoherent, a radiation element might emit only one of the OPR modes at one time. Therefore, it is possible to observe some highly linearly polarized individual pulses, while the position angles of which are 90° separated. Unfortunately, observation result similar to that of fig. 5 has never been found.

Thirdly, how to explain the non-orthogonal separation of position angles in the regime of OPM? Non-orthogonal emission modes have proverbially been found in observation[1]. These facts are rigorous for anyone to theorize OPM models.

4 Conclusion and discussion

From the analysis above some conclusions and discussions are reached:

(i) Another possible way to solve the problem of position angle 'jumps' in pulsars' beamed radio emission was proposed. There might be no real 'orthogonal polarization modes' in the emission at all.

(ii) Position angle jumps due to the observational uncertainties could appear in observed individual pulses when the linear polarization percentages are small (not only the linear polarization intensity to be small). At least part of the observed position angle jumps in individual pulses and mean-pulses can be explained by depolarization and observational uncertainty.

For a real pulsar, we must put together these two possible factors to investigate the position angle variation in the individual pulses as well as in the integrated pulses. For example, observational uncertainty might be the main reason for position angle separation near point 'A' in fig. 1. Nevertheless, near point 'C', orthogonal and non-orthogonal separations are clear, which might be the result of the relative longitude shifts of pulsar beams[6] and the observational uncertainties.

Rathnsree and Rankin[10] pointed out that, for PSR B1929 + 10, lower degree of polarization is seen simultaneously with the presence of 'orthogonal' modes, whereas the polarized power is not seen to be highly correlated with the position angle flip. Also, they have got dynamic pictures of the orthogonal polarization mode changes for PSR B2110 + 27 at 430 MHz, and they found the transition from the dominant mode to the other orthogonal one and back are rapid. Most of the transition is achieved over time scales of an individual period, and the change of modes does not seem to be any periodicity in time evolution (like a stochastic process). All these observational facts have the properties of observational uncertainties discussed in sec. 2.

For PSR B0525 + 21[1] at 1 404 MHz, the position angle sweep is S-shaped in the averaged profile. The polarization position angles in individual pulses are also an 'S' shape distribution, but two weak patches of 'orthogonal modes' on the outside edges of the profile where more individual pulses have very small percentages of linear polarization. These two patches' appearance should come of the observational uncertainty according to our analysis. This statement can be checked by future expriment of observation.

(iii) From simulations, we see that the jumped position angles are distributed near 45° and 135°. In fact, there are observational data which does show that the position angles are distributed near 45° and 135° in the scatter plots, such as figs. 26 and 37 in ref. [1]. If the rms of U is less than that of Q, the jumped position angles should be near 0° and 90°, like PSR 0525 + 21 (fig. 2 in ref. [1]) in observations. There are observational data where the jumped position angles are not distributed near 0°, 45°, 90°, and 135° , which could be intrinsic in polarimetry or resultant from the longitude shift of beam phases[6].

(iv) The idea suggested in this paper can be checked experimentally. We can input the polarimetry a simulated lower polarized and pulsed signal to see if two 90° separated position angle distribution can appear in the output. If such distribution can also the obtained, the OPM in pulsar emission should be doubted.

(v) If OPM does not exist in pulsar radio emission, we should develop our instruments to avoid observational uncertainties.

Appendix A Simulation

For the kind of polarimetry discussed in sec. 2, let us study a partially polarized wave, with the total intensity I, the un-polarized intensity I^{unp}, the percentage of linear polarization Π_1, the percentage of circular polarization Π_c, and the position angle χ. If we measure this wave by a telescope with an effective area A, systematic noise temperature S_{sys}, a bandwidth $\delta\nu$, a time constant τ, the angle between two, the dipole antenna (parasitism polarization) α (whose expectation value is $\frac{\pi}{2}$, $\delta\alpha = \alpha - \frac{\pi}{2}$, the rms of $\delta\alpha$ is σ_α), and the phase misalignment $\delta\phi$ (the rms of $\delta\phi$ is σ_ϕ), then the six intensities for the Stokes parameters can be deduced as

$$S_0 = \frac{1}{2}X^2 + \frac{1}{2}I^{\mathrm{unp}},$$

$$S_{90} = \frac{1}{2}\left(Y^2\cos^2\delta\alpha + X^2\sin^2\delta\alpha + 2XY\cos\delta\sin\delta\alpha\cos\delta\alpha\right) + \frac{1}{2}I^{\mathrm{unp}},$$

$$S_{45} = \frac{1}{4}[X^2 + Y^2\cos^2\delta\alpha + X^2\sin^2\delta\alpha + 2XY\cos(\delta - \delta\phi)\cos\delta\alpha$$
$$+ 2XY\sin\delta\alpha\cos\delta\alpha\cos\delta + 2X^2\sin\delta\alpha\cos\delta\phi] + \frac{1}{2}I^{\mathrm{unp}},$$

$$S_{135} = \frac{1}{4}[X^2 + Y^2\cos^2\delta\alpha + X^2\sin^2\varphi\alpha + 2XY\cos(\delta - \delta\phi - \pi)\cos\delta\alpha$$
$$+ 2XY\sin\delta\alpha\cos\delta\alpha\cos\delta + 2X^2\sin\delta\alpha\cos(\delta\phi + \pi)] + \frac{1}{2}I^{\mathrm{unp}},$$

$$S_R = \frac{1}{4}[X^2 + Y^2\cos^2\delta\alpha + X^2\sin^2\varphi\alpha + 2XY\cos(\delta + \delta\phi + \frac{3}{2}\pi)\cos\delta\alpha$$
$$+ 2XY\sin\delta\alpha\cos\delta\alpha\cos\delta + 2X^2\sin\delta\alpha\cos(\delta\phi + \frac{3}{2}\pi)] + \frac{1}{2}I^{\mathrm{unp}},$$
$$S_L = \frac{1}{4}[X^2 + Y^2\cos^2\delta\alpha + X^2\sin^2\delta\alpha + 2XY\cos(\delta + \delta\phi + \frac{\pi}{2})\cos\delta\alpha$$
$$+ 2XY\sin\delta\alpha\cos\delta\alpha\cos\delta + 2X^2\sin\delta\alpha\cos\left(\delta\phi + \frac{\pi}{2}\right)] + \frac{1}{2}I^{\mathrm{unp}},$$

where

$$\delta = \tan^{-1}\frac{\Pi_c}{\Pi_l\sin2\chi},$$
$$X = \sqrt{I} \times \sqrt{\sqrt{\Pi_l^2 + \Pi_c^2} + \Pi_l\cos2\chi},$$
$$Y = \sqrt{I} \times \sqrt{\sqrt{\Pi_l^2 + \Pi_c^2} - \Pi_l\cos^2\chi}.$$

The observed Stokes parameters should be

$$I' = S_0 + S_{90},$$
$$Q' = S_0 - S_{90},$$
$$U' = 2S_{45} - I',$$
$$V' = 2S_R - I'.$$

So that, the observed linear polarization intensity L', the observed percentages of linear polarization Π'_l, the observed percentages of circular polarization Π'_c, and the observed linear polarization position angle χ' would be

$$L' = \sqrt{Q'^2 + U'^2},$$
$$\Pi'_l = \frac{L'}{I'},$$
$$\Pi'_c = \frac{V'}{I'},$$
$$\chi' = \frac{1}{2}[\mathrm{sign}\,U'\cos^{-1}\frac{Q'}{L'} + \pi(1 - \mathrm{sign}\,U')].$$

Considering this kind of observational uncertainty, we have obtained some simulation results to show the position angle 'jumps' in individual pulse observations. One of the simulations is shown in fig. 4, where we have chosen

$$I = 50\ \mathrm{Jy},$$
$$\sigma_\alpha = 5°,$$
$$\sigma_\phi = 5°,$$
$$A = \pi 40^2\ \text{square meters},$$
$$S_{\mathrm{sys}} = 40\ \mathrm{K},$$
$$\delta\nu = 10\ \mathrm{MHz},$$
$$\tau = 0.3\ \mathrm{ms},$$
$$\chi = 45°,$$
$$\Pi_l = \Pi_c = \Pi = 0.01\%.$$

The scatter plots in fig. 4 are resemble to observations, especially the $L' - \chi'$ plot, which is similar to the observed linear polarization versus position angle scatter plots for position angle jumps at a fixed longitude. Based on this simulation and other simulations for different parameters, we found that the position angles 'jump' if $\Pi_1 \leqslant 0.1\%$, whereas, there are few possibilities of position angle jump if $\Pi_1 \geqslant 1\%$.

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