# Postprint of the Study on the Stability of Millisecond Pulsar Polarization Profiles

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## Abstract

Compared to normal pulsars, millisecond pulsars represent a class of neutron stars with faster rotation rates, and the pulse signals they emit possess extremely high stability. The stability of pulsar polarization profiles constitutes an important issue for investigating pulsar radiation mechanisms and the properties of the interstellar medium.

Utilizing observational data from the Australian Parkes 64;m telescope, we studied the polarization profile stability of three millisecond pulsars: PSR J1022+1001, PSR J1730-2304, and PSR J2129-5721. Through analysis of the observational data, subtle temporal variations in their polarization profiles were identified. By analyzing the causes of these profile variations, possible explanations were proposed, including the influence of the interstellar medium and instabilities in the intrinsic properties of the pulsars themselves.

## Full Text

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# Research on the Polarization Profile Stability of Millisecond Pulsars

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## ABSTRACT

Compared with normal pulsars, millisecond pulsars are a class of neutron stars with faster rotation speeds, and their emitted pulse signals exhibit extremely high stability. The stability of pulsar polarization profiles is one of the important issues in studying pulsar radiation mechanisms and interstellar medium properties. Using observational data from the Parkes 64 m telescope in Australia, we studied the polarization profile stability of three millisecond pulsars: PSR J1022+1001, PSR J1730-2304, and PSR J2129-5721. Through analysis of the observational data, we found that their polarization profiles exhibit subtle variations at different times. We analyzed the causes of these profile variations and proposed possible explanations, including the effects of interstellar scintillation and instabilities in the intrinsic properties of the pulsars themselves.



**Key words** pulsars: general, methods: data analysis, ISM (interstellar medium): general

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Studies of pulsar radiation profiles primarily fall into two categories: single-pulse profiles and average pulse profiles. Previous research has shown that the flux density, shape, and polarization characteristics of single pulses are all unstable [?]. Backer et al. [?] discovered that single pulses from some pulsars disappear in certain periods and then return to normal, a phenomenon known as pulse nulling. Studies indicate that among pulsars exhibiting nulling, older normal pulsars show more pronounced nulling than younger ones [?]. When multiple single pulses are superimposed by period, they form an average pulse profile, which is typically very stable [?, ?]. However, previous studies have still found instabilities in the average pulse profiles of some pulsars, such as mode changing [?], nulling phenomena, and subsequent phase variations [?].

Compared with normal pulsars, millisecond pulsars are used as natural clocks to study high-precision timing and related topics, such as gravitational wave detection [?], due to their more stable profiles. However, some millisecond pulsars also exhibit obvious instabilities in their integrated profiles. For example, Brook et al. [?] analyzed the pulse profiles of 38 millisecond pulsars and found significant profile variations in PSR J1713+0747, PSR B1937+21, and PSR J2145-0750, with PSR B1937+21 showing profile variations on long timescales. Mode changing typically occurs in long-period pulsars, but Mahajan et al. [?] found that the millisecond pulsar PSR B1957+20 also exhibits mode changing, with switching times between the two modes of only 1.7 s. Backer et al. [?] conducted long-term observations of PSR B1821-24 and found that approximately 25% of pulse profiles underwent significant changes. Kramer et al. [?] found that the profile instability of millisecond pulsar PSR J1022+1001 is mainly manifested in the relative intensity between its two peaks.

Many factors can cause pulsar profile variations. Shannon et al. [?] studied PSR J1713+0747 using observations from different times and with different backend processors, concluding that profile variations are mainly caused by intrinsic properties rather than instrumental effects or interstellar scattering. Ramachandran et al. [?] conducted multi-frequency observations of PSR J1022+1001's profile instability and attributed the profile variations to magnetospheric 回流 (backflow). Average pulse profiles are formed through dedispersion integration within a certain bandwidth, so profiles vary with different observation frequencies [?]. Dai et al. [?] analyzed the pulse profiles of 24 millisecond pulsars and found that the widths of pulse profiles and the separations between components exhibit complex frequency-dependent variations. Since the interstellar medium exhibits scintillation, interstellar scintillation can cause variations in pulsar radiation intensity. Cole et al. [?] first studied long-term radiation intensity variations in pulsars, finding that these variations occur on different timescales and proving that they are caused by irregular diffraction in the interstellar medium. Wang et al. [?] studied the relationship between flux density and dispersion measure for a batch of pulsars, finding a negative correlation between them. Kramer et al. [?] analyzed the effects of interstellar scintillation on single-pulse intensities through simultaneous multi-frequency observations of PSR B0329+54 and PSR B1133+16, finding that the flux density of single pulses observed at different frequencies changed. Basu et al. [?] detected long-term profile evolution in 7 out of 500 pulsars and found through simulations that the observed profile variations may originate from random variations in single-pulse shapes, also noting that such long-term profile variations are often related to linear polarization degree. Fisher et al. [?] studied the total intensity shape variations of the magnetar Swift J1818-1607, observing three mode changes and finding that the switching times between the three modes coincided with the modulation amplitude of the spin rate variation. Ables et al. [?] analyzed the pulse profiles of PSR B0833-45 at five wavelengths, finding broadening of the average pulse profile caused by interstellar medium dispersion and scattering. Wang et al. [?] analyzed the geometric parameters of 190 pulsars observed with the Five-hundred-meter Aperture Spherical radio Telescope (FAST) and found that linear polarization, circular polarization, and pulse profile width have different frequency dependencies.

Previous studies have primarily focused on variations in total intensity profiles, with few addressing the stability of polarization profiles. This paper investigates the polarization profile stability of three millisecond pulsars. Section 2 introduces the data sources and processing methods used in this study; Section 3 presents the variations in total intensity, linear polarization, and circular polarization profiles for the three millisecond pulsars; Section 4 uses simulations to analyze the causes of polarization profile instabilities; and Section 5 presents the conclusions.

## 2 Data Collection and Processing

The data used in this study come from observations with the Parkes 64 m radio telescope in Australia. The selection criteria were pulsars with strong polarization profiles and significant interstellar scintillation effects, resulting in the selection of three millisecond pulsars: PSR J1022+1001, PSR J1730-2304, and PSR J2129-5721. The observations span from August 2008 to April 2015, with each observation lasting 64 minutes, sub-integration times of 1 minute, and 2 minutes of calibration source observations before each session. To eliminate effects from different backend processors, only data from the Parkes Digital Filter Banks 4 (PDFB4) system were selected. The central observation frequency for all three millisecond pulsars was 1369 MHz with a bandwidth of 256 MHz, and the number of channels for PSR J1022+1001, PSR J1730-2304, and PSR J2129-5721 were 2048, 1024, and 512, respectively.

PSRCHIVE is specialized software for processing pulsar data, providing rich functional modules for pulsar data processing and visualization tools. This study used PSRCHIVE for post-processing of the observational data [?]. Due to the influence of narrowband and impulsive radio frequency interference, raw data in some channels may be contaminated, so these bad channels must first be removed. Additionally, data at the band edges have low gain, so the data from the outer 5% of the band edges were removed, reducing the original 256 MHz bandwidth to 230.4 MHz. The data were then calibrated using calibration files for polarization and flux density calibration, with flux density calibration processed using observations of Hydra A. Furthermore, because linear polarization is strong, it is necessary to eliminate Faraday rotation effects, using the International Reference Ionosphere (IRI) model to remove the effects of Earth' s ionosphere on Faraday rotation. All sub-integration data were then superimposed to obtain data without frequency compression. Finally, dedispersion was performed on all channel data and superimposed to obtain the polarization profile for each observation. All observed polarization profiles were superimposed to obtain a final total average polarization profile with extremely high signal-to-noise ratio.

## 3 Polarization Profile Instability

[Figure 1: see original paper] shows the total average polarization profiles and polarization position angle distributions of the three millisecond pulsars at 1369 MHz. PSR J1022+1001 exhibits a clear double-peaked structure in its total intensity profile and a triple-peaked linear polarization profile. For PSR J1730-2304, both its total intensity and linear polarization profiles show three distinct peaks. PSR J2129-5721' s total intensity profile is followed by a trailing component after the main pulse, and its linear polarization profile shows a double-peaked structure. All three millisecond pulsars show clear double-peaked structures in their circular polarization profiles.

[Figure 2: see original paper] shows two polarization profile observations with significant variations for the three millisecond pulsars, with each polarization profile intensity normalized to the maximum peak. As can be seen from the figure, the polarization profiles of these three millisecond pulsars all show some instability. PSR J1022+1001 shows obvious variations in its total intensity and circular polarization profiles, mainly manifested as changes in relative intensity between the two peaks, with the intensities of the second and third peaks of the linear polarization profile also showing significant changes. PSR J1730-2304 shows more obvious changes in the first peak of its linear polarization and total intensity profiles, with subtle variations at the peak of its circular polarization profile. For PSR J2129-5721, its total intensity profile shows little change, but the first peak of its linear polarization profile and the minimum between the two peaks change significantly, with the variation in its circular polarization profile mainly reflected in the flux density of the first peak.

The polarization profile variations of the three millisecond pulsars shown in the figure are significantly above the noise level. To investigate the causes of polarization profile variations while minimizing the impact of noise on data analysis, we selected average polarization profiles with relatively high signal-to-noise ratios for study, including 59 profiles for PSR J1022+1001, 121 for PSR J1730-2304, and 136 for PSR J2129-5721.

## 4 Analysis of the Causes of Polarization Profile Instability

Pulsar polarization profiles vary with observation frequency. The flux densities of all three millisecond pulsars decrease with increasing observation frequency, which is determined by the spectral properties of the pulsars themselves. However, because the spectral indices of each component differ significantly, the relative intensities of flux densities between components vary with frequency, leading to profile changes with observation frequency [**?**]. Interstellar scintillation causes changes in the flux density of polarization profiles at different frequency bands, and since observations are conducted within a certain bandwidth, this causes variations in the average polarization profile formed by frequency superposition. To analyze the impact of interstellar scintillation on the stability of millisecond pulsar polarization profiles, we first generated a standard polarization profile unaffected by interstellar scintillation, then simulated each observation based on the actual flux density of that observation.

### 4.1 Generating Standard Profiles

Since each observed polarization profile is affected by interstellar scintillation to varying degrees, superimposing all observed polarization profiles of the three millisecond pulsars yields a total average polarization profile that effectively eliminates the effects of interstellar scintillation. For subsequent simulation studies, the three high signal-to-noise-ratio standard profiles with 230.4 MHz bandwidth were evenly divided into 8 sub-bands, each with 28.8 MHz bandwidth, yielding high signal-to-noise-ratio polarization profiles in 8 sub-bands.

Average polarization profiles reflect the structure of pulsar radiation regions and can be considered as the superposition of independently existing individual components in the radiation region, with each component following a Gaussian distribution [**?**]. Therefore, to further eliminate noise effects, we fitted the high signal-to-noise-ratio polarization profiles in the 8 frequency bands using the following fitting function:

f ($\phi$) = aie(cid:0)4 ln 2($\phi$(cid:0)bi)2/ci

where f($\phi$) represents the fitted profile, $\phi$ represents phase, n represents the number of components in the polarization profile, i represents the ith component of the profile, a__i represents the peak of the ith component, b__i represents the phase corresponding to the peak of the ith component, and c__i represents the full width at half maximum of the ith component. This yielded analytical profiles for the 8 sub-bands. Since each sub-band is only 28.8 MHz wide and results from the superposition of multiple observations, we consider the profiles within the sub-band to be minimally affected by interstellar scintillation. Therefore, the high signal-to-noise-ratio analytical profiles in the 8 frequency bands serve as standard profiles. The fitting results for the three pulsars are shown in [Figure 3: see original paper], [Figure 4: see original paper], and [Figure 5: see original paper], respectively.

As can be seen from the figures, polarization profiles do show significant variations with frequency. For example, for PSR J1022+1001 and PSR J1730-2304, the peak ratio between the left and right peaks of the total intensity profile gradually changes from less than 1 to greater than 1 as frequency increases. The peak ratio of the linear polarization profile of PSR J1730-2304 also increases with frequency. For all three millisecond pulsars, the relative flux density between the two peaks of the circular polarization profile gradually decreases with increasing frequency. Since polarization profiles change with frequency, when pulse signals are affected by interstellar scintillation, the flux density of polarization profiles at different frequencies changes, causing the shape of the superimposed average pulse profile to be more inclined toward the profile at frequencies with higher flux density.

### 4.2 Profile Simulation and Correlation Calculation

After obtaining the standard analytical profiles, we used the analytical profile of each sub-band to simulate the polarization profile of each observation, adjusting the flux density of each sub-band's analytical profile according to the flux density of the observed profile in the corresponding sub-band, then superimposing to form the simulated profile for each observation. If each observed polarization profile is only affected by scintillation, it should be possible in principle to simulate each observation well. The simulation is calculated as follows:

F ($\phi$) = P i Rifi($\phi$)

where F($\phi$) represents the simulated profile, i represents the ith sub-band among the 8 sub-bands, R__i represents the ratio of flux density between the observed profile and the analytical profile in the ith sub-band, and f__i($\phi$) is the analytical profile fitted with a Gaussian function in the ith sub-band. The average polarization profile formed by superimposing the simulated observational data can thus be represented by the function F($\phi$). [Figure 6: see original paper] shows the simulation results for one observation of each of the three millisecond pulsars.

The degree of similarity between the observed polarization profiles and the simulated profiles in [Figure 6: see original paper] indicates the magnitude of interstellar scintillation’ s effect on the polarization profiles. For PSR J1022+1001, the total intensity and circular polarization profiles fit well, but the linear polarization profile fits the first peak well while the flux densities of the latter two peaks in the observed profile are significantly higher than in the simulated profile. For PSR J1730-2304, the total intensity and circular polarization profiles fit well, with the linear polarization profile fitting very well at the peaks but slightly worse at the troughs, where the flux density of the observed profile is significantly lower than that of the simulated profile. For PSR J2129-5721, the flux densities of the observed total intensity and linear polarization profiles at the first peak are both higher than those of the simulated profiles, the second peak fits well, and the flux densities of the circular polarization profile at both peak positions are higher than those of the simulated profile.

Since the subtle variations in each observation’ s average polarization profile are not easily discernible from the figures, we used the correlation coefficient method to describe the stability of the polarization profiles. The correlation coefficient describes the overall correlation between each observed profile and the analytical profile, with profile instability reflected in the magnitude of the correlation coefficient. The correlation coefficient is calculated as follows:

1 = i=1 (cid:128) X1i (cid:0) X1(cid:138) i=1 (cid:128) X2i (cid:0) X2(cid:138) X1i (cid:0) X1(cid:138) (cid:128) X2i (cid:0) X2(cid:138) (cid:128) i=1 (cid:128) i=1 (cid:128) Yi (cid:0) Y i=1 (cid:128) Yi (cid:0) Y i=1 (cid:128) (cid:138) Yi (cid:0) Y (cid:138) Yi (cid:0) Y (cid:138) (cid:138)

where 1 represents the correlation coefficient between the standard profile and the observed profile, 2 represents the correlation coefficient between the simulated profile and the observed profile, i represents the ith sampling point, X1i represents the flux density of the standard profile at the ith sampling point, X2i represents the flux density of the simulated profile at the ith sampling point, Yi represents the flux density of the observed profile at the ith sampling point, X1 and X2 represent the flux densities of the standard and simulated profiles, respectively, and Y represents the flux density of the observed profile.

Using the profile simulation and correlation coefficient calculation methods, we can calculate the correlation coefficients between the standard profile and each observed polarization profile, as well as between the simulated profile and each observed polarization profile. If the correlation coefficient improves after simulation, it indicates that simulating the flux density variations at different frequencies caused by interstellar scintillation works well, meaning that interstellar scintillation is the main cause of profile variations. If the correlation coefficient decreases after simulation, it indicates that scintillation has a smaller effect while other factors have a greater influence on profile variations, such as intrinsic properties of the pulsar itself.

### 4.3 Discussion

The simulation results are summarized in , which shows that interstellar scintillation affects the polarization profile stability of all three millisecond pulsars to varying degrees. For PSR J1022+1001, the linear polarization profile is most affected by interstellar scintillation, followed by the total intensity profile, with the circular polarization profile being least affected. For PSR J1730-2304, the total intensity profile is most affected by interstellar scintillation, followed by the linear polarization profile, with the circular polarization profile being least affected. For PSR J2129-5721, the effect of interstellar scintillation on its polarization profiles is opposite to that of PSR J1022+1001, with the circular polarization profile being most affected, followed by the total intensity profile, and the linear polarization profile being least affected.

At the same time, the total intensity, linear polarization, and circular polarization profiles from the same observation are affected by interstellar scintillation to different degrees, with some polarization profiles being more affected and others less. presents statistical results for cases where all polarization profiles from the same observation are significantly affected by interstellar scintillation, where only some are significantly affected, and where all are minimally affected. Cases where all three polarization profiles from the same observation of the three millisecond pulsars are simultaneously affected by interstellar scintillation are rare; in most cases, only some polarization profiles are affected, and there are also cases where all are minimally affected, indicating that the profile instability in these observations is mainly caused by other factors.

Variations in the intrinsic properties of pulsars themselves also affect polarization profile stability. The left panel of [Figure 7: see original paper] shows the total intensity profile of one observation of PSR J1022+1001. When divided into 8 sub-bands, compared with the standard profile in the right panel, the peak ratio of its total intensity profile is always greater than 1, and the polarization profiles in all 8 sub-bands have already undergone significant changes relative to the standard profile. Therefore, in this case, even when affected by interstellar scintillation, no matter how the flux density in each sub-band is simulated, the standard profile cannot fit the polarization profile of this observation well, and the same applies to the linear and circular polarization profiles. It is not difficult to see that this type of profile variation is caused by the intrinsic properties of the pulsar itself.

## 5 Conclusion

We analyzed the polarization profile stability of pulsars PSR J1022+1001, PSR J1730-2304, and PSR J2129-5721 using simulation methods. The profiles obtained from superimposing all observational data were divided into 8 frequency bands, and the polarization profiles in each band were fitted with Gaussian functions. The fitted analytical profiles in each sub-band were used as standard profiles to simulate the effects of interstellar scintillation on each observation' s polarization profile, with the changes in correlation coefficients before and after simulation used to describe the degree of influence of interstellar scintillation on polarization profile stability. The study found that interstellar scintillation affects the stability of polarization profiles, but the degree of influence varies. For PSR J1022+1001, interstellar scintillation has a greater impact on the linear polarization profile and a smaller impact on the circular polarization profile. For PSR J2129-5721, the circular polarization profile is more affected while the linear polarization profile is less affected. For PSR J1730-2304, the total intensity profile is more affected, and the circular polarization profile is less affected.

In addition to interstellar scintillation, intrinsic properties also affect polarization profile stability. When polarization profiles are divided into 8 sub-bands, there exist cases where the polarization profiles in each sub-band have already undergone significant changes relative to the standard profile. This type of profile variation may be caused by the intrinsic properties of the pulsar.

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