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First comprehensive analysis of temporal variations in spectro-polarimetric nature of pulsars

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Abstract

While the temporal variation of the spectro-polarimetric nature of pulsars remains unexplored, this investigation offers significant potential for uncovering key insights into pulsar emission mechanisms, magnetic field geometry, and propagation effects within the magnetosphere. We developed a pipeline for investigating time-varying spectral behavior for all the Stokes parameters and demonstrate it on a millisecond pulsar (MSP) J2144−5237 in a binary system (orbital period $\sim$ 10 days) using the Parkes UWL receiver. For this MSP, our study reveals clear evidence of GHz turnover, commonly referred to as Gigahertz peaked spectrum(GPS). Additionally, we observe a strong correlation between the spectra of Stokes I, Q, and linear polarization (L), a moderate correlation between Stokes I and circular polarization (V), and no significant correlation between Stokes I and U. We also provide a Poincaré sphere representation of the polarization properties of J2144−5237, demonstrating that nearby phase bins, remain clustered in the Poincaré sphere, especially for high signal to noise ratio (SNR) pulsed phase bins. To our knowledge, this is the first investigation of time-varying properties of the spectro-polarimetric nature of any pulsars or MSPs. Extending this study to probe the spectro-temporal nature of full Stokes data on a larger sample of MSPs or pulsars has the potential to provide vital information on emission mechanisms inside the magnetosphere, interstellar propagation effects, and binary interactions.

1 Introduction

Pulsars are known to be coherent emitters and highly polarized sources, hence their polarization profiles are important tools for understanding the magnetic configuration and the interaction between magnetic field and the accelerated plasma. Some of the polarization properties (e.g. rotation vector model) are very good probes for verification of dipolar magnetic field structure [1].

Spectro-polarmetric investigation of millisecond pulsars(pulsars with a spin period < 30 ms) are hindered due to their intrinsic faintness. Spectro-polarimetric studies of MSPs are essential for understanding their emission mechanisms, magnetic field configurations, and propagation effects within their magnetospheres. These studies analyze the polarization properties of pulsar emissions across various frequencies, offering insights into several key areas. Polarization profiles reveal the structure of MSP emission beams and magnetic field orientations. For instance, [10] presented high-precision polarization profiles for MSPs, highlighting their complex pulse shapes and polarization characteristics. The only way to study polarization for MSPs is to fold the data up to some time integration, up to few seconds to tens of seconds, depending on the strength of the MSPs. Variations of polarization properties (like Stokes intensity and polarization angle variation with time and frequency) help us disentangle from the intrinsic effects with the ISM (interstellar medium) or binary companion effect. To do so, we represent the Stokes parameters (Q, U, and V as defined in [2]) on the Poincaré sphere. The similar work was illustrated in [3] for FRBs.

Temporal changes in the MSP spectra was reported by [5]. Significant temporal changes in the spectra for J2144−5237 using the GMRT data was reported in this work. Advancements in broadband radio telescopes, such as the Parkes Ultra-Wideband Low (UWL) receiver and the Green Bank Telescope (GBT), have significantly enhanced the quality of spectro-polarimetric data. These improvements facilitate more detailed studies of MSP polarization properties, contributing to a deeper comprehension of their emission physics and aiding in precision pulsar timing efforts.

To the best of our knowledge, there is no extensive investigation or any attempt to study the temporal variation of the spectral nature of full Stokes parameters on pulsars. The key idea is to probe the variation of spectral nature on a large variety of time scales and associate the relevant phenomena as per the time scale of interest, like propagation effects due to ISM or surrounding medium (like: binary companion in the vicinity), and contributions intrinsic to pulsar. On top of this, such studies for MSPs, also help to understand the geometry of the region of emission inside the magnetosphere.

We conducted a spectro-polarimetric investigation of MSP J2144−5237 using Parkes UWL receiver. In Section 2 we present the telescope details used for the observations and data analysis techniques used for generating the results, and finally in Section 3 we report our findings. Section 4 presents the discussion and future scope.

2 Observations and Analysis

We observed the pulsar J2144−5237, using the UWL (ultra-wide-bandwidth low-frequency) receiver of Parkes [4]. The frequency ranges from 704 to 4032 MHz. In this paper, we present results from full polar observations on 26 July 2023 for 2.7 hrs. Other epochs of observations were taken on 5 May 2023 for 10 hrs, and 6 June 2023 for 13 hrs, and were also utilized for comparison.

We developed a pipeline that calculates spectral behavior of full Stokes parameters for various time chunks (provided by the user) as demonstrated in Figure 1. Such extensive analysis for full Stokes parameters enables us to visualize and analyze various factors influencing the polarised signal from the pulsar.

We started from the calibrated folded data cube obtained as the output of the pipeline PSRPYPE[1], which performs the polarization and flux calibration of the observed data. All the data are stored in PSRFITS format, hence we read it using astropy.io.fits and perform initial data analysis of dispersion measure (DM) corrects, baseline removal, rotation measure (RM) correction on the Stokes Q and U. After that, we calculated the spectra for Stokes I, Q, U, V, and L (linear polarization $\sqrt{Q^2+U^2}$). The Figure shows the output. The next thing is to represent the Stokes Q, U, V onto the Poincaré sphere, which also shown in the Figure.

3 Results

Figure 1 presents the spectro-polarimetric results derived from the analysis of Parkes UWL data for PSR J2144−5237, offering a comprehensive visualization of its polarization and spectral properties. The spectral and temporal variations of the Stokes parameters (I, Q, U, V) and linear polarization (L) are plotted in the first row of Figure 1. Stokes I and Q, as well as the linear polarization L, appears to decrease with time (i.e. in the first row pixel values decrease from a higher value to a lower value along the time axis). This provides valuable insight into dynamic changes in pulsar emission.

The second row presents time-averaged Stokes profiles, which offer a stable representation of the pulsar's polarization behavior over the observation period. The full-time averaged polarization profile is plotted in different panels of the second row. This row indicates that the main component and the adjacent component (to the right of the main component) have significant Stokes I signal but other Stokes parameters and linear polarization L are only observed in the main component. To facilitate the interpretation of polarization variations with the pulse phase, the same colored dots are overlaid on the Stokes I and L profiles (columns 1 and 5, respectively) and the Poincaré sphere. This serves as a reference for mapping specific phase bins onto the Poincaré sphere. The Poincaré sphere representation of Stokes Q, U, and V (presented in the last column of the second row) shows that nearby phase bins are nearby in Poincaré sphere as well. In other words, profile components are clustered in the Poincaré sphere.

The first study of temporal changes in spectra of the MSPs was presented by [5]. To explore potential temporal variations within 2.7 hrs of observing duration, we divide the observation into three distinct time segments and present the corresponding time-averaged spectral information in the last three rows of Figure 1. The spectra of total intensity plotted in the first column of the third-row show evidence of GHz turnover around 1.2 GHz, commonly referred to as Gigahertz peaked spectrum(GPS). Some pulsars exhibit GHz-peaked spectra, which could be linked to propagation effects, magnetospheric effects, binary interactions, supernova reminant or pulsar wind nebulae interaction with the surrounding medium [6, 9]. However, to our knowledge, this is the first evidence for observations of the GPS on full Stokes parameters for any MSP. Understanding spectral turnovers provides clues about cyclotron absorption, synchrotron self-absorption, or free-free absorption in MSP environments [7]. Identifying full polar GPS behavior in MSPs can provide insights into their evolutionary pathways and binary interactions [8]. We note that with time there is an indication of shift of the turnover frequency of the spectrum towards the lower radio frequencies (shift in the peak of Stokes I in the first column for time chunks 0, 1, 2, in Figure 1). Detailed investigation of the possible correlation of the peak frequency (as referred to in GPS phenomena) with the orbital phase can provide vital clues towards explaining MSP full Stokes spectra as well as the origin of GHz turnover.

Moreover, the correlation (similarity in the trend of 2-dimensional plot of some of the Stokes parameters with L) can be observed in the first row of Figure 1 where, we observe a high correlation between Stokes I, Q, and L, a mild correlation between Stokes I and V, and no correlation between Stokes I and U (spectra for U is rather flat) for this epoch. We also analyzed other available epochs for this MSP, and plots similar to Figure 1 are located in the footnote[2]. The detailed understanding and implication of the features obtained in other epochs are still in progress.

4 Discussion

Investigation of spectra and polarization are two fundamental blocks for understanding the properties of the MSPs. In this work, we combine these two components and present the method for the first time-varying investigation of the spectro-polarimetric properties for any pulsar so far. We have successfully applied this method on the MSPs J2144−5237, and the main new results from this work are listed in the following:

(i) The spectra of Stokes I and Q exhibit a strong correlation with the linear polarization spectra along frequency and time, whereas the Stokes U spectrum remains relatively flat, indicating that the correlation between total intensity and linear polarization is primarily driven by Stokes Q. Our objective is to investigate how propagation effects influence the spectral behavior of different Stokes parameters, particularly their distinct manifestations in Stokes Q and U. For circular polarization (Stokes V), we observe a mild correlation with both total intensity and linear polarization.

(ii) For the first time we observed full Stokes GHz turnover for any MSP. These GPS pulsars are often situated in complex environments, such as pulsar wind nebulae or super-

[1] `https://github.com/vivekvenkris/psrpype`

[2] `https://drive.google.com/drive/folders/13g3g-q9b0S1U0GTeE_nWsz6kEJtIlWb2?usp=sharing`

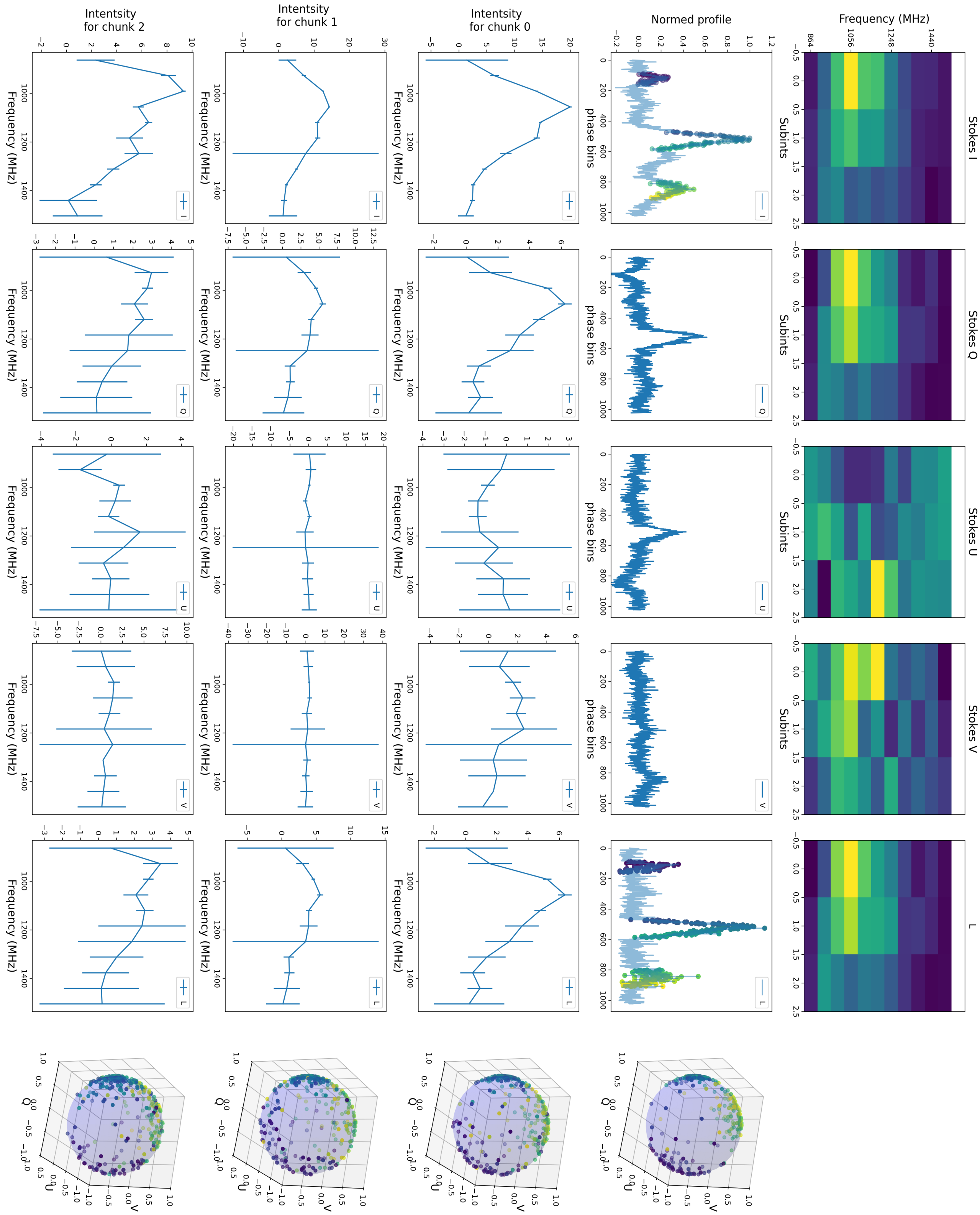

Figure 1. The plot presents the Spectro-polarimetric results obtained from analysis of Parkes UWL data for PSR J2144−5237. The columns display Stokes parameters (I, Q, U, V), linear polarization (L), and a Poincaré representation of Stokes Q, U, and V. The first row shows spectral-temporal variations, while the second row provides time-averaged Stokes profiles and the corresponding Poincaré sphere. The coloured dots, in the second row, in the Stokes I and L profiles (columns 1 and 5, respectively) serve as a visual aid for mapping the phase bin points onto the Poincaré sphere. The last three rows display time-averaged spectra for different data segments (data divided into three time segments) and the corresponding Poincaré sphere representations.

nova remnants, where thermal free-free absorption or synchrotron self-absorption mechanisms are believed to cause the observed spectral turnovers [7].
(iii) We have observed temporal evolution of the spectra for MSP J2144−5237 during the observing span of 2.7 hours. The temporal changes in flux density modulation of Stokes I, Q and linear polarization L as well as the circular polarization V seem to be correlated (decreasing at the end of the observing span). Whereas for Stokes U we observe that flux density to be increasing towards the end of the observing span.
(iv) A Poincaré sphere representation of the Stokes I, Q, U and V is presented, showing nearby phase bins are clustered together. The scatter increases for individual time chunks (the last 3 rows) as compared to full time averaged point on the sphere (second row). The trajectory of points on the Poincaré sphere reveals how polarization changes across the pulse phase. Nearby phase bins in the pulse profile tend to remain clustered on the sphere, indicating smooth variations in polarization.

Following are the future plans,
(i) Investigation of spectro-polarimetric properties of J2144−5732 at different time chunks and disentangling the effect of the environment responsible for the GHz peaked spectrum.
(ii) Conduct investigation of time varying nature of spectro-polarimetric properties for a bigger sample of MSPs and normal pulsars using wider frequency range (i.e. perform simultaneous observations, wherever possible, using low (LOFAR, uGMRT), mid (uGMRT, MeerKat) and high-frequency (Meerkat, Effelsberg) radio telescopes).
(iii) Modelling the temporal variation of spectro-polarimetric properties and probe for clues for disentangling intrinsic effect (through profile component dependent analysis), surrounding medium effect (through sub-integration dependent analysis), and the interplay of the two (thorough spectro-temporal changes in the Stokes parameters).
Thus in summary, we present new results from a hitherto unexplored regime of temporal changes in spectro-polarimetric properties of MSP J2144−5237 and will be applied to a larger sample of pulsars.

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