Polarization variation near eclipse for spider MSP J1242−4712

Ankita Ghosh[(1)], Bhaswati Bhattacharyya[(1)], Sangita Kumari[(1)], Rahul Sharan[(1)]
(1) National Centre For Radio Astrophysics, Tata Institute of Fundamental Research, Pune 411007, India

Abstract

We present the polarization study for spider millisecond pulsar (MSP) J1242−4712 with the observations from the Parkes telescope. This is an interesting system with an orbital period of 7.7 hrs and minimum companion mass 0.08 $M_\odot$ sharing properties of both black widows and redbacks. We found a substantial linear polarization for this MSP for non-eclipse phases. We also performed the orbital phase-resolved analysis of the polarization fraction for this system and observed depolarization near the pulsar's superior and inferior conjunction indicating the presence of a strong magnetic field in the eclipse region, which has been seen for other such eclipsing spider systems.

1 Introduction

PSR J1242−4712 was discovered with the GMRT High-Resolution Southern Sky Survey[1] [2, 3] by Bhattacharyya et al. (in prep). The pulsar has a pulse period of 5.31 ms and a dispersion measure of 78.6 pc/cc. From the timing analysis spanning over 4.5 years of observations, we found that PSR J1242−4712 has an orbital period of 7.7 hrs and orbiting a companion of minimum mass 0.08 $M_\odot$, occupying a relatively unexplored region in the orbital period versus companion mass space [8].
In these compact systems, the intense pulsar wind can wear away the companion star [12, 18] resulting in the creation of MSP binaries with very low-mass companions. These MSPs with mostly hydrogen-rich, non-degenerate companions in compact binary orbits (orbital periods $< 1\,$d) are classified as "spider MSPs", and are further divided by companion mass M_c into "black widow (BW)" ($M_c < 0.05 M_\odot$) and "redback (RB)" ($0.1 M_\odot < M_c < 0.9 M_\odot$) spiders [25, 26].
The highly energetic wind from the pulsar ablates the companion, leaving ionized material in the orbit which causes an eclipse of the pulsar's radio emission. The majority of spider MSP systems exhibit frequency-dependent eclipses, which appear more pronounced at lower frequencies than higher ones, often absent above ∼1.5 GHz [13, 21]. PSR J1242−4712 eclipses for a very short duration near superior conjunction of pulsar between orbital phase 0.23−0.25, below 360 MHz. In addition to the eclipse near the superior conjunction of the pulsar, we have also seen a mini eclipse near orbital phase 0.18 below 360 MHz [8]. Moreover, a clear signature of eclipsing is also observed for this MSP near the pulsar's inferior conjunction in band-4 (orbital phase ∼ 0.7, in one of the epochs causing an excess DM delay and large error in pulses time of arrivals (TOAs) as also seen for redback MSP J1227−4853 [13]. The observed mini eclipses indicate temporal clumping of the materials throughout the binary orbit which has also been observed in other such systems [6]. Observed eclipses and significant orbital period variability suggest that PSR J1242−4712 is possibly not a He−WD binary, but has a semi- or non-degenerate companion, indicating that this is a "spider" MSP lying in a region between typical black widows and redbacks.
Understanding eclipse mechanisms sheds light on pulsar radiation and interactions with companions. There are many proposed eclipse mechanisms and different mechanisms may be responsible for different systems; for example, refractive effects [18], pulse smearing [27], cyclotron and synchrotron absorption [7, 29], induced scattering [16], and free–free absorption [31, 23, 24]. Stappers et al. (2001a) [28] and Polzin et al. (2019) [20] analyzed PSR J2051−0827, suggesting pulse scattering and cyclotron damping as possible eclipse mechanisms. Kansabanik et al. (2021) [11] found synchrotron absorption could explain frequency-dependent eclipses in PSR J1544+4937 by modeling the broadband radio spectrum in the optically thick-to-thin transition regime. Also, Kumari et al. 2023 [14] investigated frequency-dependent eclipsing for around 40 eclipses for the black widow PSR J1544+4937 using GMRT data between 300 MHz − 750 MHz; and observed a temporal change of cutoff frequency.
Polarization properties are indicative of the pulsar's local environment. The observed pulsar radiation goes under Faraday rotation, characterized by rotation measure (RM), as it propagates through the interstellar medium. By measuring the RM from pulsar emission, we can calculate the galactic magnetic field along various lines of sight through the interstellar medium. As the observer's line of sight traverses the core of the emission beam, the linear polarization position angle (PPA) also rotates and appears as an S-shaped sweep. It gets interesting for spider MSPs as tracking the evolution of RM and PPA swings can lead to constraints on the dynamic state of the ablated material in the orbit. Recent polarisation studies and plasma lensing predictions of magnetic field intensity at eclipse ingress and egress give rise to an added dilemma [15, 19, 4].

[1] http://www.ncra.tifr.res.in/~bhaswati/GHRSS.html

Crowter et al. (2020) [4] measured RM changes near PSR J2256−1024's eclipse boundary, estimating a line-of-sight magnetic field of ∼1.11 mG. Li et al. (2019) [15] inferred a line-of-sight magnetic field strength $< 0.02G$ near PSR B1957+20's eclipse boundary due to plasma lensing. The magnetic field strength at eclipse ingress and egress found by either of these methods is several orders of magnitude lower than the required magnetic field strength to sustain pulsar wind ram pressure. The magnetic field obtained by observing the change in RM in the eclipse ingress and egress phase can be compared to the magnetic field estimated by modeling eclipse phase spectra using wide-band observations.

Motivated by this, we present the polarization properties of spider pulsar PSR J1242−4712 using the observations from Parkes 64 m radio telescope. Our observations and analysis methods are described in Section 2. In Section 3 we investigate how the pulsar's polarization properties vary as functions of orbital phase. We discuss and summarize our conclusions in Section 4.

2 Observations and Data analysis

Table 1. Summary of observations

Backend	T^a_{res} (μs)	F^b_{res} (MHz)	Bandwidth (MHz)	Centre frequency (MHz)
Parkes UWL Medusa	5.189	1.0	3368	2368

Notes.
^{a}: Time resolution
^{b}: Frequency resolution

We have observed MSP J1242−4712 with Parkes UWL in two epochs May 29 2023 and June 22, 2023. Observations of 29th May 2023 have a duration of 2 hours only. Observations of June 22, 2023, span over nearly 7 hours probing almost the full orbit of the pulsar in one epoch. We have analyzed this data of MSP J1242-4712 to study the polarization properties throughout the pulsar's orbit. A summary of these observations is provided in Table 1. All the data were coherently de-dispersed, with a frequency resolution of 1 MHz and a time resolution of 5.189 μs. We took a brief observation (∼ 5 min) of a phase calibrator source before each observation. The first round of RFI mitigation was carried out using the pipeline[2] and then the remaining RFI was manually mitigated in the time and frequency domain. Subsequently, we calibrated the data using the PSRCHIVE [10] task "PAC". Due to the lower Signal to noise ratio, we averaged across frequency and phase bins by factors of 8, using the PSRCHIVE task "PAM". This resulted in a calibrated folded profile comprising 4 Stokes parameters, 416 frequency channels, and 128 phase bins for each epoch. Consecutive observations from 22 June 2023 excluding the eclipse region were combined using the PSRCHIVE task "PSRADD", generating a single output file. A time drift observed in the combined file was rectified by updating the parameter file. This involved fitting the time of arrivals (TOAs) calculated using the PSRCHIVE task "PAT", solely for spin frequency (F0), the epoch of ascending node (T0), and projected semi-major axis (A1) using tempo2 [9]. We used this combined average profile from the non-eclipse phase to obtain the average polarization fraction and rotational measure (RM) of the pulsar. For the flux density calculations versus the orbital phase, we have determined the area under the integrated pulse.

[2] https://github.com/vivekvenkris/psrpype/

3 Results

We have obtained the integrated polarization profile (Figure 1) for J1242−4712 by adding the observations of the non-eclipse phase, which are calibrated and RM corrected. We found the best fit RM value is −3.92 ± 1.09 from the integrated average profile of the pulsar. The average pulse profile has three components at this frequency, although only the main component shows linear polarisation (nearly 18%). We used the lower part of the frequency band (728−960 MHz) to calculate polarization and RM as the MSP is not too faint above that and not visible above 2000 MHz. We could not measure RM for each orbital phase due to low SNR. The polarization position angle is rather flatter, as seen for some of the other MSPs [5]. We also analyzed

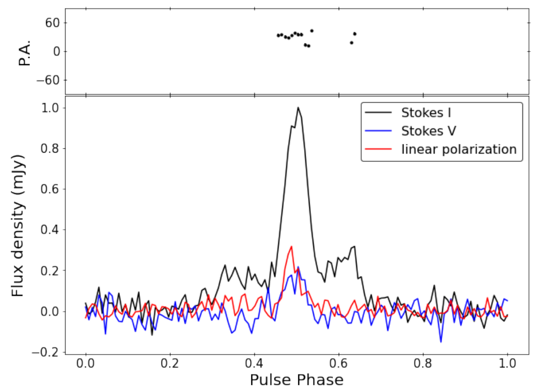

Figure 1. Polarization profile of J1242−4712

the variation of intensity and polarization fraction as a function of the orbital phase to investigate evidence of eclipsing. Though the eclipse itself wasn't visually observed at this frequency, we could observe the effect of the eclipse through a decrease in total intensity and polarization fraction around superior (orbital phase, 0.22−0.26) and inferior conjunction (orbital phase, 0.69−0.75)(shaded region in Figure 2). The orbital phase-dependent flux density is calculated by considering the lower part of the band, with a central frequency of 815 MHz and a bandwidth of 232 MHz.

Depolarization during the eclipse phase has been observed in spider MSPs; for example, PSR J2051−0827 by Wang et al. (2023), PSR J2256−1024 by Crowter et al. (2020) [4], and J1748−2446A by You et al. (2018) [33]. This depolarization can occur due to the multipath propagation of pulsed radiation through the circumstellar magnetized plasma leading to rapid time variations in the RM. Such rapid RM variations can result from fluctuations in either or both of the circumstellar components of dispersion measure (DM) and the parallel component of the magnetic field. DM variations are observed at both eclipse ingress and egress for eclipsing spider pulsars. However, these variations are typically very low, which will not significantly affect the RM [33]. We investigated the orbital phase-dependent DM variation for PSR J1242−4712 and observed a slight increase in the DM value during the eclipse phase (around ∼0.2 and ∼0.85 orbital phase), however not very significant. The excess DM and the corresponding electron column density (N_e) as the function of orbital phase is determined from the delay in time of arrival of pulses (obtained using tempo2) using the relation,

$$DM_{excess}\ (pc\ cm^{-3}) = 2.4\times 10^{-10} \times \text{TOA delay}(\mu s) \times f^2(MHz) \quad (1)$$

where TOA delay is the time delay in μs and f is the observing frequency in MHz. From DM_{excess} the N_e is computed using:

$$\text{Excess}\ N_e\ (cm^{-2}) = 3\times 10^{18} \times DM_{excess}(pc\ cm^{-3}) \quad (2)$$

The variation of DM as a function of the orbital phase is illustrated in Figure 3. These DM variations are found to be of the order $\sim 10^{-5}$ cm^{-3} pc for J1242−4712, which will not significantly affect the RM. Therefore, short-timescale variations in the line-of-sight magnetic field can cause depolarization through rapid fluctuations of RM in time, indicating that there might be a significant magnetic field in the eclipse medium. This fluctuation of the magnetic field is common in the turbulent stellar wind.

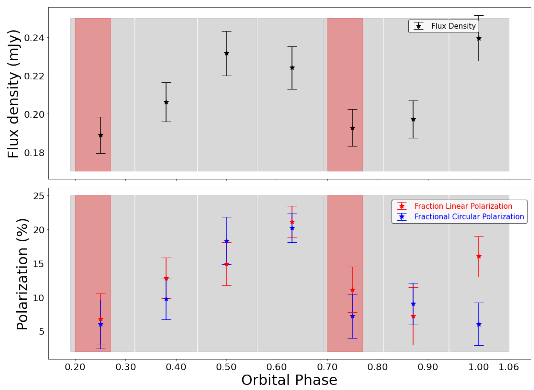

Figure 2. Intensity and linear and circular polarization variation with orbital phase. Each point corresponds to 60 min of integration. The error was estimated by taking a 5% error in flux calibration. Red-shaded regions correspond to the eclipse phases at superior and inferior conjunction.

We have seen an eclipse below 360 MHz for this MSP at superior conjunction (orbital phase ∼0.23−0.25 along with excess dm delay and large error in pulse's time of arrivals at inferior conjunction (orbital phase ∼ 0.7) at the frequency range 300-750 MHz with uGMRT. Interestingly, at

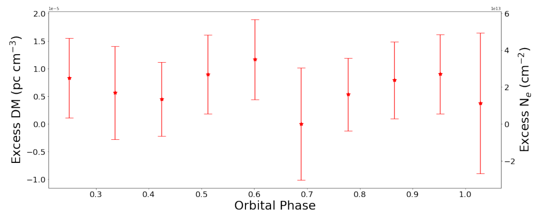

Figure 3. Excess DM and electron density variation with orbital phase

815 MHz, when observed with Parkes, the eclipse was not observed. However, even at this higher frequency, the effects of the eclipse are still noticeable. Therefore, a comprehensive investigation into orbital phase-resolved wide-band spectra, as done by Kansabanik et al. 2021 [11], can aid in better understanding and constraining the eclipse mechanism.

4 Conclusions

Radio emission from pulsars is known to be significantly linearly and circularly polarized. Polarization studies reveal the local magneto-ionic environment of a pulsar. Rotation Measure (RM) shows the averaged magnetic strength parallel to the line of sight in the intervening plasma. MSPs are particularly interesting in their polarization characteristics. It is found that the degree of polarization is higher compared to the normal pulsars [32]. Polarization Position Angle (PPA) for normal pulsars (with spin period >30 ms) generally exhibits an "S" shape swing, which can be explained by the Rotating Vector Model (RVM, [22]). For a sample of 24 MSPs, Dai et al. [2015] observed extremely complicated PPA variation that is difficult to explain with the RVM model. The S-curve trace of PPA is also used to determine the geometry of pulsars and the radio emission heights [17]. However, PPA swings for MSPs are flatter, suggesting a different model to explain the PPA evolution over the pulse profile. Following up a sample of MSPs and studying their polarization properties can lead to better constraints on the evolution and emission mechanisms for MSPs. While explaining the PPA swings using the RVM model, the degeneracy between alpha (angle between the magnetic axis and rotation axis) and beta (angle between the line of sight and the magnetic axis) can be constrained. We observed MSP J1242-4712 with Parkes UWL, probing the full orbit in one epoch. We observed a change in polarization fraction with the different orbital phases of this MSP. Though the eclipse was not seen at this frequency (700-2000 MHz), we observed the memory of the eclipse in the form of flux fading and linear depolarization in both the eclipse phases near superior and inferior conjunction. This is an interesting finding for the probing eclipse mechanism. Moreover, probing the DM and RM variation near eclipse egress and ingress with low-frequency observations, where MSP is much brighter, can be useful to constrain the linear depolarization observed near the eclipse region along with the magnetic field.

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