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Drastic change in the eclipse cutoff frequency for PSR J1544+4937 observed with the GMRT

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Abstract

We report a very drastic change in the eclipse cut-off frequency for the black widow pulsar J1544+4937. Majority of such systems often exhibit relatively long duration ($\sim$ 15%) radio eclipses caused by ablated material from the companion stars. The eclipse observed in such systems are frequency dependent and are more pronounced at lower frequencies ($<$ 1.5 MHz). The eclipse cutoff frequency has changed from 345 MHz to $>$ 750 MHz. Such an intense change in the eclipse cutoff frequency is not observed and reported for any other spider MSPs before. This shows that PSR J1544+4937 is clearly undergoing some kind of transition, where the eclipse environment is dynamically evolving. Follow-up observations showed that the system is coming back to its normal state, where the eclipse cutoff frequency is $<$ 550 MHz. This change in the eclipse cut-off frequency could depict changes of the magnetic field and drastic change in electron density in the eclipse region.

1 Introduction

Millisecond pulsars (MSPs) are thought to evolve from normal pulsars by accreting matter from the companion star (1). This idea is supported by the observations, where most ($>$ 80%) of the MSPs are found in the binary orbits. Around 30 % of these are in very compact binary orbits (orbital period $P_b <$ 1day). These systems are known as spider MSPs (2). Based on the mass of the companion (m_c), spider MSPs are further divided into two categories: redback ($0.1M_\odot < m_c < 0.9M_\odot$) and black widow ($m_c < 0.1M_\odot$). Being in such a compact orbits, the pulsars in these systems are more prone to interactions with the companion where the highly relativistic wind from the pulsar ablates the companion star. As a result of which majority of these systems often exhibit relatively long duration ($\sim$ 15%) radio eclipses where the ablated material from the companion star blocks the low frequency radio waves from the pulsar (3). The eclipses seen are frequency dependent and the eclipses are more pronounced at lower frequency compared to high frequencies, mostly not seen at high frequencies ($>$1.5 MHz).

PSR J1544+4937 is a Fermi BW MSP with spin period 2.16 ms (4) discovered by the Giant Metrewave Radio Telescope (GMRT, (5)). This pulsar is in a tight binary orbit having orbital period of 2.16 hours with low mass companion star of minimum mass $m_c = 0.017\ M_\odot$ (4). The first eclipse study for this system was done by (4). They observed the binary system with legacy GMRT 32 MHz bandwidth system (5) centered at 322 and 607 MHz. Eclipse was seen at 322 MHz where the signal from the pulsar was obscured for $\sim$13% of the orbit, although no eclipse was observed at 607 MHz. (4) concluded that synchrotron absorption is the possible eclipse mechanism and that the eclipse cut-off frequency lies between 322 to 607 MHz. Later detailed studies were done by (6) with 200 MHz wide bandwidth upgraded GMRT (7) system. They modeled the broadband radio spectrum in the optically thick to thin transition regime using multi frequency observations to constrain the eclipse mechanism which favors synchrotron absorption by relativistic electrons. They also concluded that the eclipse cut-off frequency is 345 $\pm$ 5 MHz.

From our recent observations we have found an intense change in the eclipse cut-off frequency for this system. Such variation in the eclipse cutoff freqency is not observed or reported for any BW MSPs before. In this paper the details of the observations and the data analysis are discussed in Section 2. In Section 3 the results and conclusions for PSR J1544+4937 are detailed.

2 Observations and data analysis

The observations reported in this paper are performed with the upgraded GMRT (7) system, which is a radio interferometric array consisting of 30 dishes, each of 45 meter in diameter. The observations were divided in 3 observing epochs : 12th Feburary 2022, 28th June 2022 and 08th July 2022 by the splitting the antennas into two sub arrays at 300-500 MHz and 550-750 MHz. All the observations presented in this paper were preformed using the coherently array mode. Coherent beam filterbank data at best achievable time-frequency resolution were recorded.

We have used radio frequency interference (RFI) mitigation software, GMRT pulsar tool (gptool; A. Chowdhury et al, in preparation) to mitgate the narrow-band and short duration broad-band RFI. We have then corrected for the interstellar dispersion using incoherent dedispersion technique and folded the time series with the known radio ephemeris for PSR J1544+4937 from

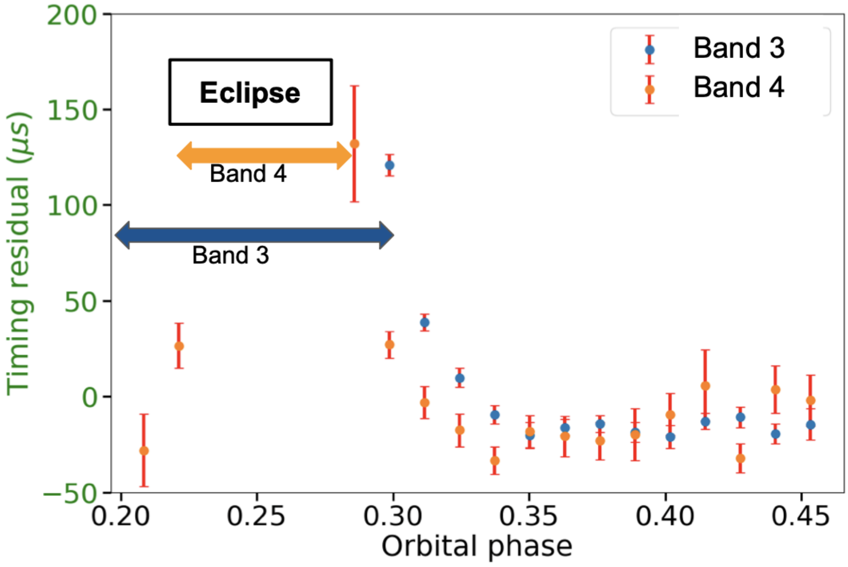

Figure 1. Timing delay observed for band 3 and band 4 for the observation on 12th February 2022. At band 3 the eclipse is seen for longer duration (9%) of the orbit compared to band 4 (4%)

Table 1. Summary of the observations

Observing epoch	Backend	Cut-off frequency (MHz)	Column density (cm^{-2})
10 June 2012"	legacy GMRT	-	8×10^{-16}
06 February 2018†	uGMRT	345 ± 5MHz	5×10^{-16}
12 February 2022‡	uGMRT	$\geq$ 750MHz	1.5×10^{-16}
28th June 2022‡	uGMRT	$\geq$ 750MHz	$1 \times 10^{-16*}$
08th July 2022‡	uGMRT	410 MHz	2×10^{-16}

" (4)
† (6)
‡ this work
* Column density is evaluated using the band 3 observation, as the detection significance has decreased even before the eclipse phase in band 4 (Fig 4).

(4) utilizing prepfold task of PRESTO (8). The obtained mean pulse profile is cross-correlated with the template profile (high signal to noise profile from the previous observations). The temporal shift between these two profiles yielded the observed time of arrivals of the pulses (TOAs). The TOAs are generated using a python script getTOAs.py from PRESTO (8). We have used tempo2 software package (9) to calculate the timing residual which is the difference between the observed and predicted TOAs. From the timing residual plots given in Fig 1, the excess time delay (t_{excess}) at the eclipse boundary is observed. Using this delay the excess dispersion measure (DM_{excess}) at the eclipse boundary can be determined using the relation :

$$\mathrm{DM_{excess}} = 2.4 \times 10^{-10} \mathrm{t_{excess}}(\mu \mathrm{s}) \mathrm{f}^2(\mathrm{MHz}) \tag{1}$$

From the $\mathrm{DM_{excess}}$ the electron column density in the eclipse medium is computed using :

$$\mathrm{N_e(cm^2)} = 3 \times 10^{18} \times \mathrm{DM(pc\ cm^{-3})} \tag{2}$$

The plot of electron column density as the function of orbital phase at band 4 is given in Fig 2 for 12th February 2022. The observed eclipse is frequency dependent and is less pronounced in band 4 compared to band 3 (Fig 1). As the eclipse region can be probed deeper in band 4, we estimated an lower limit on the electron column density for 12th February 2022 using the band 4 observations of 5×10^{16} cm^{-2} in the eclipse medium. The corresponding electron volume density is 7×10^5 cm^{-3}.

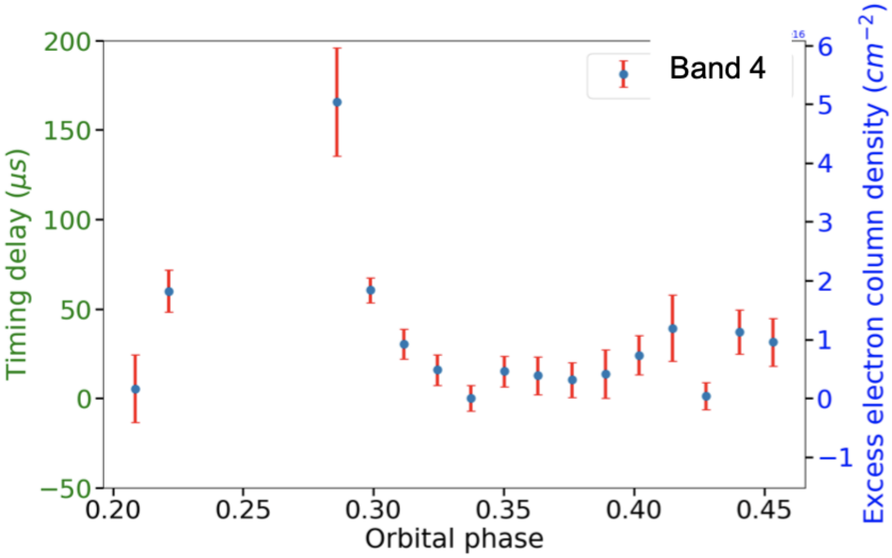

Figure 2. Timing delay observed for band 4 and the corresponding electron column density for observation on 12th February 2022.

3 Results

3.1 Change in the eclipse cut-off frequency

From our recent observation on 12th February, a very drastic change in the eclipse cut-off frequency is seen. We report an two fold increase in the cut-off frequency, where the cut-off frequency has raised from 345 MHz to $\geq$ 750 MHz. The detection prepfold plots of PSR J1544+4937 for the observations on 12th February 2022 is shown in the Fig 3. The eclipse can be clearly seen for whole band 3 and band 4 of uGMRT, depicting a cutoff frequency of $\geq 750\ MHz$. Considering the eclipse cut-off frequency of 750 MHz we have applied the possible eclipse mechanisms prescribed by (10) to explain our observation on 12th February 2022 in the following:

3.1.1 Plasma frequency cut-off

The radio signal from the pulsar will not be detected if the frequency of the radio waves from the pulsar is less than the plasma frequency of the eclipsing medium. We have estimated the lower limit on the electron density in the eclipsing medium of $\mathrm{n_e} = 7 \times 10^5\ \mathrm{cm}^{-3}$. Using this value of $\mathrm{n_e}$ the plasma frequency is $\mathrm{f_p} = 8.5\ (\frac{\mathrm{n_e}}{\mathrm{cm}^{-3}})^{1/2}$ KHz $= 7\ MHz$. This value of the plasma frequency is far lower than the observed cut-off frequency. Therefore plasma frequency cut-off could not explain the observed eclipse on 12th February 2022, unless there is a sharp increase in the electron density at the superior conjunction in the eclipse medium.

3.1.2 Refraction of radio waves

Refraction of radio waves from the pulsar away from our line of sight, could also give rise to the observed eclipse. For refraction to explain the observations, the timing delay of $10-100$ ms are required (10). The observed timing delay on 12th February 2022 are in μs, thence refraction cannot explain the observed eclipse.

3.1.3 Scattering of the radio waves

Scattering of the radio waves by the free electrons in the eclipsing medium can also give rise to the eclipse. Scattering leads to pulse broadening as the scattered waves arrives late compared to the non scattered radio waves. If the pulse broadening exceeds the spin period of the pulsar, then the pulsar would not be detected giving rise to eclipse. Scattering is frequency dependent and becomes less pronounced at higher frequencies. To explain the cut-off frequency of 345 MHz (6) discarded pulse broadening as the major eclipse mechanism. Therefore, to explain the higher cut-off frequency of $\geq 750\ MHz$, we also reject scattering of radio waves as the responsible eclipse mechanism.

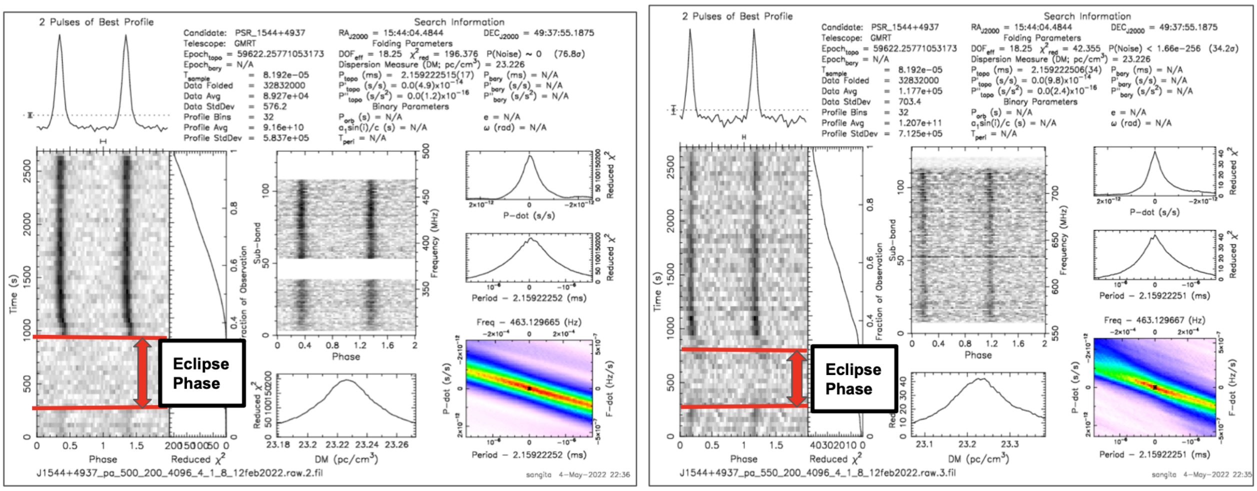

Figure 3. Prepfold detection 12th February 2022 (with the eclipse phase marked in red). Left: band 3 ; Right : band 4. As can be clearly seen that the eclipse is observed at entire band 3 and band 4. The likely cut-off frequency is $\geq 750MHz$.

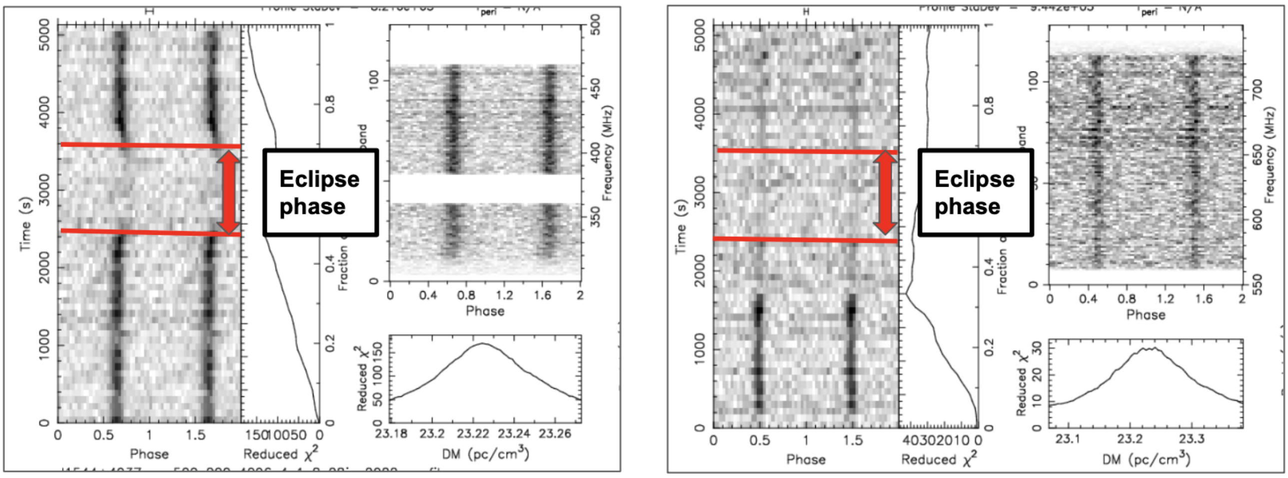

Figure 4. Prepfold detection 28th June 2022 (with the eclipse phase marked in red). Left: band 3 ; Right : band 4. As can be clearly seen that the eclipse is observed at entire band 3 (cut-off frequency >345 MHz) and flux fading is observed at band 4 even after the eclipse phase. The likely cut-off frequency is $\geq 750MHz$

3.1.4 Free-free absorption

The optical depth for free-free absorption is given as (10):

$$\tau_{\rm ff} = 3.8 \times 10^{14} \left(\frac{\rm f_{cl}}{\rm T^{3/2} \nu^2 L} \right) \rm N_e^2 ln(5 \times 10^{10} (\frac{T^{3/2}}{\nu})) \tag{3}$$

where, f_{cl} is the clumping factor, T is the temperature of the eclipse medium, ν is the cut-off frequency, L is the absorption length, N_e is the electron column density in the eclipse medium. For absorption to take place $\tau_{\rm ff} << 1$. Using ν = 750 MHz, L = 1 $R_\odot$, $N_e = 5 \times 10^{16}\ cm^{-2}$ and $\tau_{\rm ff} \leq 1$, we get the condition $T \leq 183 f_{cl}^{2/3}$. Therefore for absorption to take place either very low temperatures ($T < 1000\ K$) or very high clumping factor is required ($f_{cl} = 10^9$). The pulsar radiation is itself intense enough to heat the plasma beyond this required temperature value and also such high clumping factor is not feasible. As a result, free-free absorption can also not explain the observed eclipse on 12th February 2022.

3.1.5 Induced compton scattering

This process this called induced as the reaction rates are proportional to number of rays taking part in the interaction. The reaction rates are higher compared to spontaneous reaction rates. The optical depth for induced compton scattering is given as

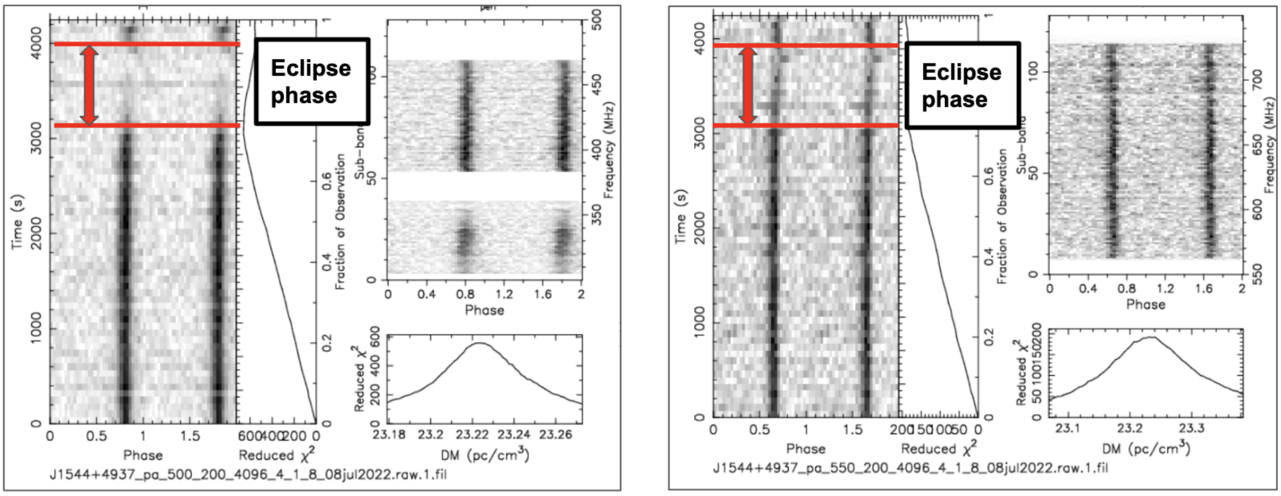

Figure 5. Prepfold detection 8th July 2022 (with the eclipse phase marked in red). Left: band 3 ; Right : band 4. As can be clearly seen that the eclipse is observed at band 3 (cut-off frequency > 345 MHz, but it would < 500 MHz) and flux fading is observed at band 4 (cut-off frequency < 550 MHz). The likely cut-off frequency is $\geq 410 MHz$.

(10):

$$\tau_{ind} = 4 \times 10^6 (\frac{N_e S_\nu}{\nu^2}) |\alpha + 1| (\frac{d_{kpc}}{a})^2 \tag{4}$$

where N_e is the electron column density, S_ν is the flux density at frequency ν, α is the spectral index, d_{kpc} is the distance to the pulsar, a is the distance between the pulsar and the companion. We have considered α to be -2 and using this we get S_ν at 750 MHz to be 1 mJy, considering the flux density at 400 MHz to be 5.4 mJy ((4)). The distance is taken to be 2.9 kpc (DM distance) and a is considered to be 1.2 $R_\odot$. Using the above values, we get $\tau_{ind} < 1$. Therefore induced Compton scattering cannot explain the observed eclipse at 750 MHz.

3.1.6 Cyclotron absorption

Since, the eclipse region is magnetised, cyclotron absorption could also be responsible for the observed eclipse, where the non-relativistic electrons may absorb radio waves at cyclotron frequency or its lower harmonics. The cyclotron frequency is given by$\nu_c = \frac{eB}{2\pi m_e c}$. The eclipse cutoff frequency is ≥ 750 MHz. Therefore, the corresponding cyclotron harmonic ($\frac{\nu}{\nu_c}$) is 25, using the characteristic magnetic field as 10 Gauss (6). If we assume the angle of magnetic field with our line of sight is 90 deg then, only the contribution from perpendicular component of the optical depth will be prominent and is given by (10):

$$\tau^m_{abs\perp} = \frac{\pi}{2} \frac{m}{m!} \left(\frac{mkT}{2m_e c^2} \right)^{(m-1)} \frac{n_e e^2 L_B}{m_e c \nu} \tag{5}$$

where k is the Boltzmann constant, m_e is the electron mass, e is the electron charge, L_B is the scale length of magnetic field variations. Assuming magnetic field scale length is similar to electron density variation, we have $n_e L_B = N_e$. The cyclotron approximation is valid for,

$$m \leq \left(\frac{2kT_e}{m_e c^2} \right)^{-\frac{2}{3}} \tag{6}$$

We calculated the temperature of the eclipse medium from equation (5), assuming $\tau^m_{abs\perp} \geq 1$,

$$T \geq 9.7 \times 10^7 K \tag{7}$$

For cyclotron approximation to be valid the required temperature $T \leq 1.9 \times 10^5 K$ (using equation (6)). Clearly, the eclipse medium temperature estimated in equation (7) is not consistent with the above temperature requirement for cyclotron approximation to be valid. Therefore, cyclotron absorption could also not explain the observed eclipse.

3.1.7 Synchrotron absorption

The eclipse medium does contain the relativistic electrons along with the magnetic field. Together they can give rise to synchrotron absorption of the radio waves. Both the thermal and non thermal electrons can give rise to the synchrotron absorption.

The absorption is dominated by the non-thermal electrons if $m > \frac{1}{2}(p+1)$ (10), where p is the spectral index of electron distribution $n(E) = n_o E^{-p}; E_{min} < E < E_{max}$. The optical depth is given by (10):

$$\tau_{abs} = \left(\frac{3^{\frac{(p+1)}{2}} \Gamma(\frac{3p+2}{12}) \Gamma(\frac{3p+22}{12})}{4} \right) \left(\frac{\sin\theta}{m} \right)^{\frac{p+2}{2}} \frac{n_o e^2}{m_e c \nu} L \tag{8}$$

where θ is the angle of the magnetic field lines with our line of sight, L is the absorption length.

(4) and (6) found for their observations that the synchrotron absorption is the major cause giving rise to the eclipse. Assuming that synchrotron absorption is the most probable mechanism for our observations too, we calculated the magnetic field strength required to explain such a high cut-off frequency. Using L = 1 $R_\odot$, $n_o = 7 \times 10^3$ (assuming non thermal electron density is 1% of the total electron density in the eclipse medium, (10)), $\theta = 45\,\mathrm{deg}$, we get B $>$ 3 Gauss.

3.2 Follow-up observations

PSR J1544+4937 system was followed up to check the status of the eclipse cut-off frequency. Two observations were taken on 28th June 2022 and 08th July 2022.The detection plots for observation on 28th June 2022 is shown in the Fig 4. The eclipse is clearly seen for the whole band 3 and band 4 at the superior conjunction. In band 4 the signal is weak even after and before the eclipse, the reason for the same is yet to be investigated. The detection plot for the observation on 08th July 2022 is shown in Fig 5. For this observation the eclipse is seen for a part of band 3, but in band 4 eclipse is not seen throughout the band. For the inspection of signal in the eclipse region we divided the total 200 MHz bandwidth into smaller 20 MHz band. For each 20 MHz bandwidth we examined the signal in the eclipse region (orbital phase 0.2-0.35). If the detection significance in the eclipse region is less than 1 sigma then, we considered it as no detection. For 08th July 2022, we found that the cut-off frequency is around 407 $\pm$ 20 MHz. This change in the cut-off frequency clearly depicts that the eclipse environment is dynamically evolving.

4 Summary

We have seen a very extreme change in the eclipse cut-off frequency for PSR J1544+4937 from our observations on 12th February 2022. The eclipse cut-off frequency has changed from 345 $\pm$ 5 MHz (6) to $\geq$ 750 MHz. This implies that the eclipse medium is varying with time. Observed changes in the cut-off frequency suggests temporal changes in the conditions of the eclipse medium including the changes in magnetic field strength and electron number density. Follow up observations on 28th June 2022 and 08th July 2022 showed that the system may slowly be coming back to its earlier state of lower cutoff frequency (345 MHz). Such an intense change in the eclipse cut-off frequency is not reported for any other BW MSPs. The summary of the results is shown in Table 1. We are in the process of taking more observations of this system, to check the status of the eclipse cut-off frequency for this pulsar.

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