

The Magnetic Field of the Solar Corona from Pulsar Observations

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Abstract We present a novel experiment with the capacity to independently measure both the electron density and the magnetic field of the solar corona. We achieve this through measurement of the excess Faraday rotation resulting from propagation of the polarised emission from a number of pulsars through the magnetic field of the solar corona. This method yields independent measures of the integrated electron density, via dispersion of the pulsed signal and the magnetic field, via the amount of Faraday rotation. In principle this allows the determination of the integrated magnetic field through the solar corona along many lines of sight without any assumptions regarding the electron density distribution. We present a detection of an increase in the rotation measure of the pulsar J1801-2304 of approximately 170 rad m^2 at an elongation of 0.96° from the centre of the solar disc. This corresponds to a lower limit of the magnetic field strength along this line of sight of $>41.8 \text{ nT}$. The lack of precision in the integrated electron density measurement restricts this result to a limit, but application of coronal plasma models can further constrain this to approximately $0.5 \text{ } \mu\text{T}$, along a path passing 2.7 solar radii from the solar limb, which is consistent with predictions obtained using extensions to the source surface models published by the Wilcox Solar Observatory.

Keywords Sun: magnetic field

1. Introduction

Our understanding of the solar corona is far from complete. Attempts are continually being made to marry theory and observations, but these efforts are hampered by the difficulty in

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obtaining direct measurements of physical properties throughout the corona. Without these measurements the state of the corona must be inferred from models that extrapolate from those observations that can be obtained from the solar surface or at distances comparable to 1 AU. Experiments have attempted to probe the outer corona via Faraday rotation through a variety of methods including measuring the rotation of the position angle of polarised emissions from the *Cassini* spacecraft (Jensen *et al.*, 2005) and *Pioneer 6* (Levy *et al.*, 1969). Background radio sources have also been used to constrain the mean integrated line-of-sight magnetic field (Mancuso and Spangler, 2000). We have used the coaxial 10/50 cm receiver attached to the 64-m Parkes radio telescope to observe a number of pulsars as the background radio sources. As indicated by Bird *et al.* (1980), pulsars have a number of advantages over the background sources observed successfully by Mancuso and Spangler (2000). Pulsars are polarised point sources and the position angle (PA) of any linearly polarised component is routinely measured by pulsar observers; their radiation is also broadband and pulsed, allowing simultaneous observation at multiple frequencies and the direct determination of the electron density along the line of sight.

This method has been motivated by the success of the *Cassini* and background radio source experiments and can in principle present a unique opportunity to disentangle the two properties of the solar corona that contribute to any observed rotation measure (RM): Namely, by measuring the dispersion of the pulsar signal we can determine the coronal electron density independently, thereby allowing the path-integrated magnetic field to be uniquely determined without recourse to a theoretical model of the coronal density profile. Consequently, we can determine whether any variations in observed RM are due to fluctuations in the field or variations in electron density. This has not been possible in the previous experiments of this nature. A further motivation is the large number of simultaneous lines of sight through the corona that can be observed within a given session; therefore the three-dimensional structure of the corona can be constrained to a considerable degree.

We carried out this experiment in December 2006, detecting a large variation in rotation measure for one target and smaller variations in the second target. No variation was detected in our calibrator pulsar, demonstrating the feasibility of the experiment and convincing us of the veracity of our results.

This paper is structured in the following manner. We first present the level of the effect we intend to measure, determining this via a simple model magnetic field constructed from a potential field model using data from the Wilcox Solar Observatory and a model of the coronal electron density. We then discuss the details of the experimental method. We finally present the results of the experiment, together with the calibration observations.

2. Experimental Justification

To explore the feasibility of this experiment we have constructed a relatively simple model solar corona, using a potential field model and separate electron density model. This construction was then used to examine the level of the expected variations in rotation measure and dispersion measure.

2.1. The Potential Field Model

Many approaches to model the solar magnetic field have been taken, the earliest being the potential field model developed independently by Schatten, Wilcox, and Ness (1969) and Altschuler and Newkirk (1969), which extends photospheric measurements from magnetograms out to a *source surface*, typically $2.5 R_{\odot}$ from the centre of the Sun. It is generally

not considered wise to simply extrapolate from the field values at this surface out to arbitrary radii, as we have done here. This however, is not intended to be a perfect model of the field in the outer corona, but a general model that maintains the geometry of the field and provides approximate values for the field in a “typical” quiet Sun.

Following Altschuler and Newkirk (1969), the potential field model begins with the assumption that the coronal field is supporting no currents, which is equivalent to

$$\nabla \times \mathbf{B} = 0. \tag{1}$$

The magnetic field can therefore be represented as the negative gradient of the scalar potential ψ ,

$$\mathbf{B} = -\nabla\psi. \tag{2}$$

Since

$$\nabla \cdot \mathbf{B} = 0, \tag{3}$$

then

$$\nabla \cdot \nabla\psi = 0, \tag{4}$$

which is equivalent to

$$\nabla^2\psi = 0. \tag{5}$$

Therefore the potential satisfies Laplace’s equation. A solution of Laplace’s equation can be found in terms of Legendre polynomials. In this case we have used a series of Schmidt quasi-normalised Legendre polynomials. The potential field solution decomposed into spherical polar components r , θ , and ϕ , where θ is the colatitude, is of the following form:

$$B_r = \sum_{lm} P_l^m(\cos\theta)(g_{lm} \cos m\theta + h_{lm} \sin m\theta) \times \left((l+1) \left(\frac{R_\odot}{r}\right)^{l+2} - l \left(\frac{r}{R_s}\right)^{l-1} c_l \right), \tag{6}$$

$$B_\theta = -1 \times \sum_{lm} \left(\left(\frac{R_\odot}{r}\right)^{l+2} + \left(\frac{r}{R_s}\right)^{l-1} c_l \right) \times (g_{lm} \cos m\theta + h_{lm} \sin m\theta) \frac{\partial P_l^m(\cos\theta)}{\partial\theta}, \tag{7}$$

$$B_\phi = \sum_{lm} \left(\left(\frac{R_\odot}{r}\right)^{l+2} + \left(\frac{r}{R_s}\right)^{l-1} c_l \right) \frac{m}{\sin\theta} \times (\cos\theta)(g_{lm} \sin m\theta - h_{lm} \cos m\theta) P_l^m(\cos\theta), \tag{8}$$

where

$$c_l = -\frac{R_\odot}{R_s}, \tag{9}$$

R_s is the distance to the source surface ($2.5 R_\odot$ in this case), R_\odot is the solar radius, and the coefficients h_{lm} and g_{lm} are tabulated by the Wilcox Solar Observatory for the rotation corresponding to the epoch of our experiment.

2.2. An Electron Density Model

We have applied the same electron model used by Mancuso and Spangler (2000). This is a two-component model introduced by Guhathakurta, Holzer, and MacQueen (1996). The two components are a coronal hole and an equatorial streamer belt. The equatorial streamer is confined to the region of zero magnetic field (the solid line in Figure 1).

The two components in the Mancuso and Spangler (2000) version of the Guhathakurta, Holzer, and MacQueen (1996) model are designated n_{CS} and n_{CH} , the *current sheet* and the *coronal hole*. They are combined in the following manner to obtain the total electron density:

$$n(r, \theta, \phi) = n_{CH}(r) + [n_{CS}(r) - n_{CH}(r)] \exp[-\theta^2/w^2(r, \phi)], \tag{10}$$

where w represents the width of the streamer and θ is the angular distance in latitude above or below it. Here,

$$n_{CH}(r) = \left[16.15 \left(\frac{r}{R_\odot}\right)^{-4.39} + 9.975 \left(\frac{r}{R_\odot}\right)^{-4.09} + 1.099 \left(\frac{r}{R_\odot}\right)^{-2} \right] \times 10^5, \tag{11}$$

and the streamer (n_{CS}) is given by

$$n_{CS}(r) = \left[365 \left(\frac{r}{R_\odot}\right)^{-4.31} + 3.6 \left(\frac{r}{R_\odot}\right)^{-2} \right] \times 10^5, \tag{12}$$

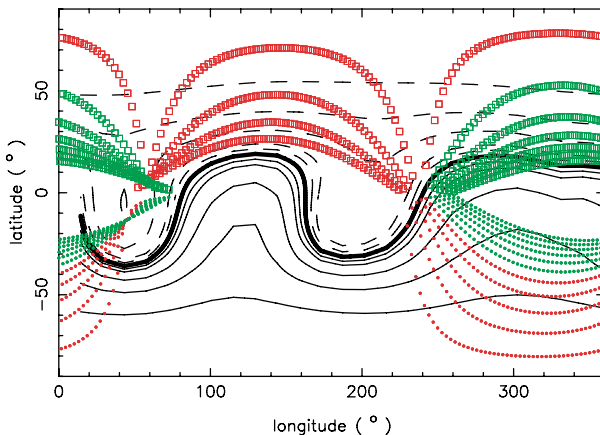


Figure 1 The radial component of the magnetic field of the Sun at a distance of 2.5 solar radii from the centre of the Sun, calculated using the sum of quasi-Schmidt normalised Legendre polynomials and using coefficients supplied by Wilcox Solar Observatory for Carrington rotation 2051. The contour lines are 0, ± 1 , 2, 5, 10, 20 μT , the solid black line being the neutral line. The boxes represent the lines of sight to J1801-2304, the dots are lines of sight to J1757-2421, the red symbols denote lines of sight between 22 and 23 December, and the green symbols denote lines of sight between 23 and 24 December.

Table 1 Possible targets.

	Pulsar name	Ecliptic longitude : latitude	Flux (mJy) at 1400 MHz
	J1652-2404	254.73 : -1.50	1.1 ^a
	J1721-2457	261.18 : -1.81	unknown
	J1730-2304	263.19 : 0.19	4 ^b
	J1733-2228	263.86 : 0.821	2.3 ^d
	J1753-2501	268.52 : -1.576	2.3 ^d
	J1756-2251	269.26 : 0.57	0.6 ^e
	J1756-2435	269.30 : -1.1554	2.0 ^d
	J1757-2421	269.42 : -0.9307	3.9 ^d
	J1757-2223	269.50 : 1.04	1.1 ^c
	J1759-2205	269.86 : 1.3467	1.3 ^d
	J1759-2302	269.96 : 0.40	1.3 ^c
	J1801-2304	270.31 : 0.36	2.2 ^d
^a Lorimer <i>et al.</i> (1995).	J1803-2137	270.89 : 1.8282	7.6 ^d
^b Kramer <i>et al.</i> (1998).	J1807-2459A	271.66 : -1.57	1.1 ^d
^c Morris <i>et al.</i> (2002).	J1817-2311	273.91 : 0.20	unknown
^d Hobbs <i>et al.</i> (2004).	J1822-2256	275.28 : 0.392	2.4 ^d
^e Faulkner <i>et al.</i> (2005).	J2048-1616	310.12 : 1.49	13 ^a

with the electron density being measured in cm^{-3} . We have made the assumption in this model that the streamer is $\pi/16$ rad in half-width, which is consistent with the value of $12^\circ \pm 2^\circ$ used by Mancuso and Spangler (2000).

2.3. The Pulsars

The ecliptic plane is tilted with respect to the Galaxy; therefore twice a year the Sun passes through the Galactic plane as it is projected on the celestial sphere. The known pulsar population is preferentially distributed within the Galactic plane and interrogation of the ATNF pulsar database (Manchester *et al.*, 2005) has provided a list of pulsars that pass close to the Sun (within 2.5°) that are grouped in ecliptic longitude and display appreciable flux in the frequency bands of interest. These pulsars are listed in Table 1. We only attempted observations of a small subset of these pulsars, but they are all included in the table for completeness.

2.4. Pulsar Observations

Pulsars are point sources of periodic broadband noise. A pulsar observation consists of an integration, lasting typically hundreds or thousands of pulse periods, which is folded modulo the topocentric pulse period to obtain a pulse profile. Pulsar emission is in general polarised, but different pulsars display different degrees of circular and linear polarisation. The position angle of linear polarisation varies through the pulsar profile but is stable in time.

Changes in the Faraday rotation to which the radiation from pulsars is subjected during passage through the solar corona manifests itself as a rotation of the polarisation angle of linear polarisation. This change in position angle is a function of frequency and is apparent

both across the band and between observing bands. A change in the electron content along the line of sight manifests itself as a dispersive delay between the arrival of the pulse at different frequencies.

2.5. Measuring Dispersion and Rotation Measure

In routine pulsar observations the ionised content of the interstellar medium (ISM) results in a dispersive delay between pulse arrival times at different frequencies. For this experiment there is a further delay because of the electron content in the solar corona. Although this is a small effect it is measurable if the same pulse can be observed over a considerable frequency interval. Measurement of this delay provides an independent measure of the electron content along the line of sight from the following relation:

$$\Delta t = \frac{e^2}{2\pi m_e c} \times \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \times \int_0^d n_e dl, \quad (13)$$

which is generally expressed as

$$\Delta t \approx 4.15 \times 10^6 \text{ ms} \times \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \times \text{DM}, \quad (14)$$

where both frequencies are in megahertz and the dispersion measure (DM) is expressed in $\text{cm}^{-3} \text{ pc}$.

The rotation measure is defined as

$$\text{RM} = \frac{e^3}{2\pi m_e^2 c^4} \times \int_0^d n_e \mathbf{B} \cdot d\mathbf{l}. \quad (15)$$

The total Faraday rotation is integrated along a path, and the total angular rotation in polarisation position angle is given by

$$\Delta\Phi = \lambda^2 \times \text{RM}. \quad (16)$$

It is readily appreciated that if both RM and DM can be measured then the integrated magnetic field strength along the path can be obtained via

$$\langle B_{\parallel} \rangle = 0.123 \text{ nT} \left(\frac{\text{RM}}{\text{rad m}^{-2}} \right) \left(\frac{\text{DM}}{\text{cm}^{-3} \text{ pc}} \right)^{-1}. \quad (17)$$

3. The Experiment

3.1. Observations

The observations were carried out using the Parkes radio telescope between 20 and 28 December 2006. Of the pulsars listed in Table 1 we observed PSRs J1801-2304, J1757-2421, J1757-2223, and J1822-2256. Of these, only the first two were useful for this experiment; the latter two had very low linear polarisation and it was very difficult to measure an accurate RM. We also observed a calibrator pulsar, PSR J1644-4559, whose properties are well known (Johnston, 2004) and which is far enough away from the Sun to undergo no changes in its parameters.

We observed at three different wavebands, 50, 20, and 10 cm, using two different receiver packages. The first was the H–OH receiver at a central frequency of 1369 MHz with a bandwidth of 256 MHz. We also used the 10/50 cm receiver, a dual-frequency system capable of observing simultaneously at both 650 and 3000 MHz. We used central frequencies of 3100 MHz with bandwidths of 512 and 690 MHz with an effective bandwidth (after interference rejection) of 35 MHz.

All receivers have orthogonal linear feeds and also have a pulsed calibration signal that can be injected at a position angle of 45° to the two feed probes. A digital correlator was used to subdivide the bandwidth into 1024 frequency channels and provide all four Stokes parameters. We also recorded 1024 phase bins per pulse period for each Stokes parameter. The pulsars were observed for ≈ 30 min on each occasion and prior to the observation of the pulsar a 3-min observation of the pulsed calibration signal was made. The data were written to disc in FITS format for subsequent off-line analysis.

Data analysis was carried out by using the PSRCHIVE software package (Hotan, van Straten, and Manchester, 2004) and the analysis and calibration were carried out in an identical fashion to that described in detail in Johnston *et al.* (2005b). Most importantly, we are able to determine absolute position angles for the linearly polarised radiation at all three of our observing frequencies.

3.2. Results

The absolute polarisation calibration at all three observing frequencies allows us to obtain a more accurate RM in the following way. First, we obtain the RM through fitting to the PAs of the linear radiation as a function of observing frequency across the band at a single frequency. We then improve the RMs by comparing PAs between the different frequency bands, where the large lever arm yields a much smaller error bar. Unfortunately, this is not possible for PSR J1801-2304 because the pulsar is essentially invisible at our lowest frequency. To compute an accurate value of RM for this pulsar we used the 1.4 and 3.1 GHz data initially, and then used changes at 3.1 GHz to measure changes in RM relative to this value. The ionosphere also contributes to the measured RM, and changes in the ionospheric conditions can cause the apparent RM to vary. These effects are at the ± 2 rad m⁻² level and do not concern us here.

The dispersion measure was computed by first measuring the time of arrival of the pulsar as a function of frequency across the observing band. Then Equation (14) was fitted in the arrival times to determine an accurate value of DM.

Results for PSRs J1757-2421 and J1801-2304 are shown in Tables 2 and 3, respectively. Both pulsars have RMs previously measured. The value obtained for PSR J1801-2304 is -1156 ± 20 rad m⁻² (Crawford, Manchester, and Kaspi, 2001), consistent with our measurements. PSR J1757-2421 has an RM quoted as 153 ± 12 rad m⁻² by Hamilton and Lyne (1987) and -9 ± 9 by Han *et al.* (2006). The value from the first authors is in error and should in fact be 0 ± 12 rad m⁻² (A. Lyne, private communication). There is a surprising difference between the two cases. For PSR J1757-2421, the RM of the pulsar far from the Sun is -26 rad m⁻², consistent with, but more accurate than, the Han *et al.* (2006) result, and we only see deviations from this value at a single epoch (20 December). For PSR J1801-2304 in contrast we see significant variations from day to day. The RM of the pulsar far from the Sun is -1150 rad m⁻² and this value was also obtained once the pulsar was more than 5° from the Sun. However, on 23 December, when the pulsar was less than 1° from the Sun's centre, we recorded an RM change of approximately 170 rad m⁻². On 22 December, the date of the closest approach to the Sun, the total intensity of the pulsar was low (likely

Table 2 Results for PSR J1757-2421.

Date	Elongation (degrees)	DM (cm^{-3} pc)	RM (rad m^{-2})
20 Dec.	1.89	179.5 ± 0.12	-33 ± 2
21 Dec. ^b	1.10	177.4 ± 0.5	-26 ± 2
22 Dec. ^a	1.11	–	–
23 Dec.	1.96	179.9 ± 0.2	-26 ± 2
24 Dec.	2.88	179.8 ± 0.2	-26 ± 2
28 Dec.	8.43	179.4 ± 0.06	-26 ± 2

^aNot observed.^bVery weak.**Table 3** Results for PSR J1801-2304.

Date	Elongation (degrees)	DM (cm^{-3} pc)	RM (rad m^{-2})
20 Dec.	2.60	1071.9 ± 0.4	-1170 ± 7
21 Dec. ^a	1.50	–	–
22 Dec. ^b	0.44	–	–
23 Dec.	0.96	1070.1 ± 0.5	$0 -977 \pm 7$
24 Dec.	1.84	1069.2 ± 0.4	-1145 ± 74
25 Dec.	2.91	1070.0 ± 0.3	-1160 ± 7
27 Dec.	5.11	1070.2 ± 0.4	-1158 ± 7

^aNot observed.^bVery weak.

caused by an increase in the system temperature because of the proximity to the Sun) and we were unable to determine an RM value.

This is an extremely high RM variation, although not unprecedented in the pulsar literature. PSR B1259-63 is in an eccentric orbit about a Be star companion (Johnston *et al.*, 1992). During the periastron approach, the RM changes significantly, reaching a peak variation in excess of 10^4 rad m^{-2} (Connors *et al.*, 2002; Johnston *et al.*, 2005a). This change implies that the magnetic field in the vicinity of the Be star is ≈ 6 mG.

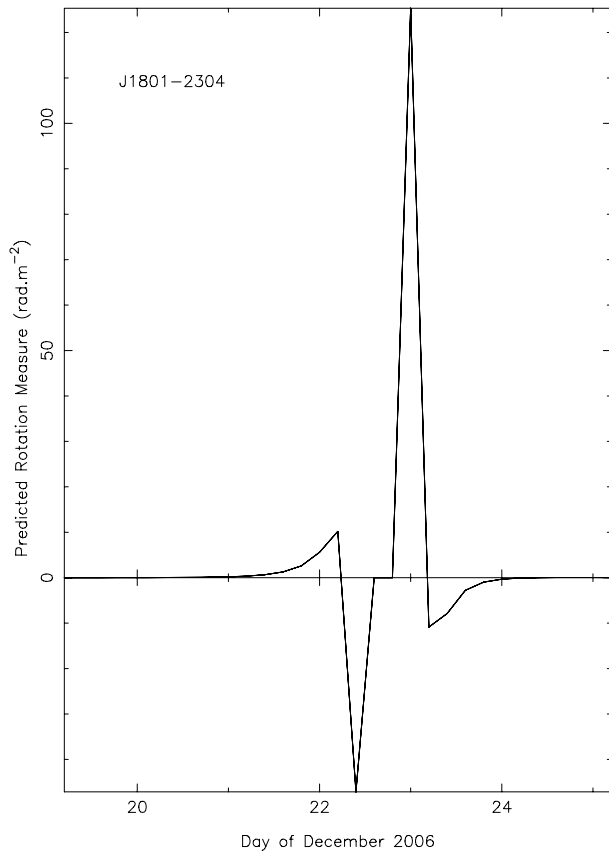
3.3. Predictions

The simple models described in Section 2 have been used to model this experiment. The line of sight to each pulsar as the Sun moves across the sky has been projected through the model solar corona and the change in measured electron content and excess Faraday rotation has been predicted as a function of observing day. Figure 2 presents the expected Faraday rotation at the three observing wavelengths. The predictions indicate that a large change in rotation measure for PSR J1801-2304 was actually expected for the days in question. However, the observed RM change is higher even than the prediction, suggesting that our simple model is not fully describing the state of the magnetosphere. The predictions suggest that an even greater effect would have been observed toward the end of 22 December; however, as noted previously, observations taken on that day has a signal-to-noise ratio too low to detect a variation in RM.

3.3.1. Rotation Measure

The modelling has revealed that the expected level of position angle rotation is incredibly variable, as a function of both observing day and ecliptic latitude. This is due to the geometry

Figure 2 The predicted excess Faraday rotation for PSR J1801-2304. The pulsar was observed throughout this period; unfortunately the observation at the height of the predicted Faraday rotation has insufficient signal-to-noise ratio to allow a confirmation.



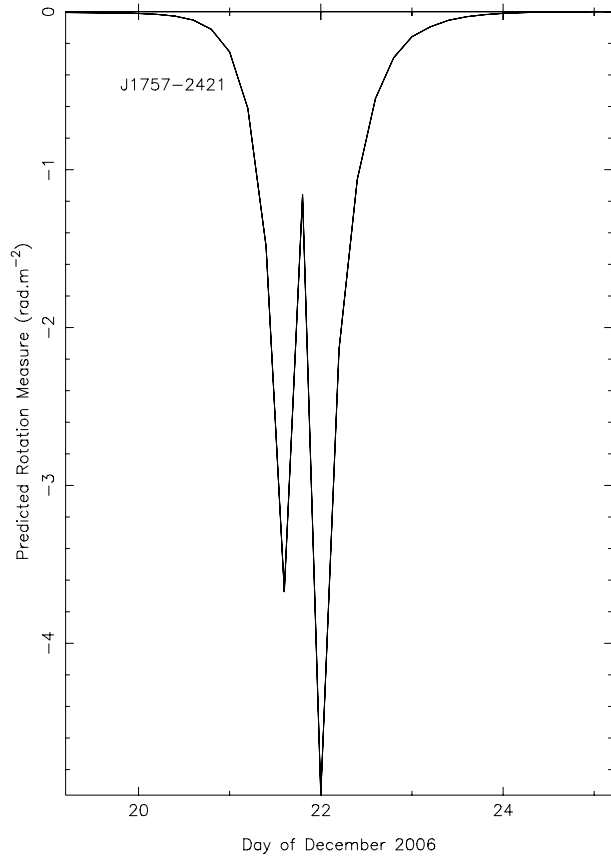
of the coronal magnetic field. If the line of sight to the pulsar projects through a symmetric coronal magnetic structure then the resultant RM will be negligible. However, if the solar corona is asymmetric the RM, and thus the rotation in PA, can be considerable. Figure 2 shows this clearly; there is essentially no rotation in the PA except for one day within the two-week period simulated in the figure. The results are not unprecedented. Mancuso and Spangler (2000) indicate variable measured RM (from 0 to 11 rad m^{-2}) at a considerable distance from the Sun and Ingleby, Spangler, and Whiting (private communication, 2007) detect an RM change of 61 rad m^{-2} at a distance greater than 5 solar radii.

PSR J1757-2421 also passes close to the solar limb; however, it does not display significant excess Faraday rotation. The explanation is provided by Figure 3, which indicates that the expected Faraday rotation is very low. This is due to the line of sight traversing a generally symmetric field configuration, which can be discerned from Figure 1.

3.3.2. Dispersion Measure

The essential difference between this experiment and that performed by Mancuso and Spangler (2000) is that we are observing simple polarised point sources with a single dish and that we can independently measure the electron component in the coronal plasma. Pulsar observations typically consider the solar wind as a source of an additional dispersive delay to that imposed upon observations by the interstellar medium. In analysing pulse times of

Figure 3 The predicted excess Faraday rotation for PSR J1757-2421. The line of sight to this pulsar traverses regions of the corona that are symmetric in their magnetic field and electron properties; therefore it displays little net Faraday rotation.



arrival one typically attempts to remove the additional delay imposed by the solar wind by assuming a very simple model of the solar corona (see Lommen *et al.*, 2006 for a discussion). This has long been considered a gross simplification by the pulsar community and work is currently underway to greatly improve upon the current model (Edwards, Hobbs, and Manchester, 2006). Inadequacies in the current model have been apparent as periodic DM variations in timing observations of some pulsars; for example, Splaver *et al.* (2005) present a periodic DM variation of $2 \times 10^{-4} \text{ pc cm}^{-3}$ for the pulsar J1713+0747. Our predictions indicate a level of DM variation at 10 times this level ($\text{few} \times 10^{-3} \text{ pc cm}^{-3}$) for some objects, as presented in Figure 4. This will be challenging to measure for some of the pulsars in Table 1, as the arrival time precision is not high.

Changes in DM of order $10^{-3} \text{ pc cm}^{-3}$ require a timing precision of several microseconds at both 0.7 and 3.1 GHz simultaneously. Timing arrival precision is given, as a rough rule of thumb, by the width of the pulse divided by the signal-to-noise ratio of the observation. As most of the target list have widths of order 10 ms, high signal-to-noise ratios will be required to obtain the required measurement precision. However, some of the target pulsars, notably the millisecond pulsars PSR J1730-2304 and PSR J1756-2251, have a pulse width of order 1 ms and such should allow sufficient measurement precision.

Experiments that probe the solar corona electron density using pulsar occultation have been successfully performed in this past (Counselman and Rankin, 1972, 1973; Weisberg

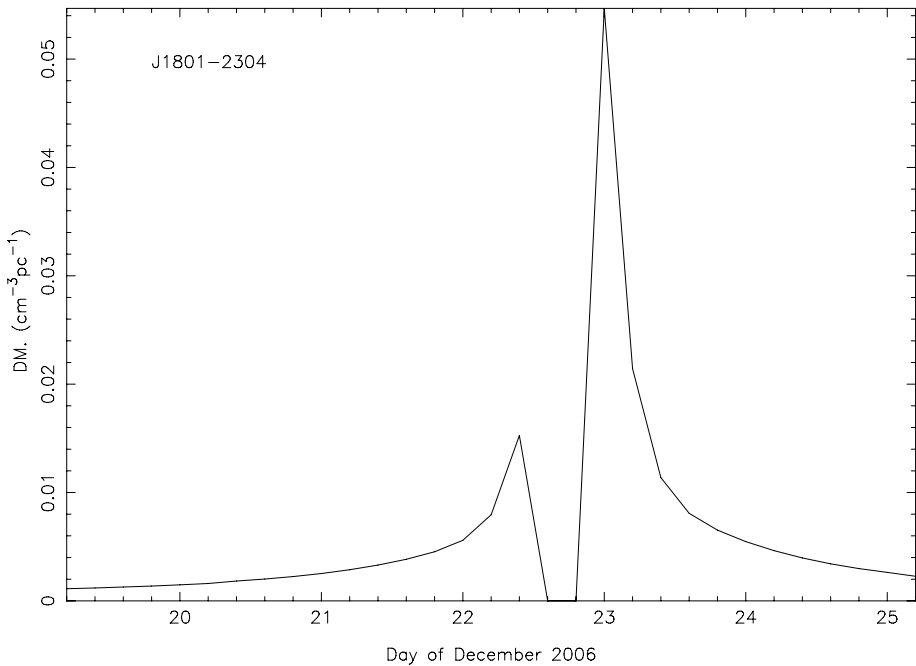


Figure 4 The expected DM variations for J1801-2304.

et al., 1976). A much lower frequency (100 MHz) was generally employed where the pulse dispersion delay effect is larger, and where measurements of multipath propagation delay can also aid in measurement of the electron density. But such low frequencies do not permit observations as close to the solar disc as required by the current experiment.

We were unable to detect any variation in dispersion measure for J1801-2304 owing to a lack of precision in pulse time of arrival. Figure 4 indicates the expected level of DM variation and as can be seen from Table 3 our DM measurement accuracy falls a long way short.

3.4. Magnetic Field

The dispersion measure precision presented in Table 3 is $0.5 \text{ cm}^{-3} \text{ pc}$; any DM contribution from the plasma of the solar corona must be less than this. We can therefore use this limit to indicate a minimum magnetic field [using Equation (17)] of $>41.8 \text{ nT}$. Under the assumption that the coronal plasma model outlined in Section 2.2 and shown in Figure 4 is a reasonable representation of the coronal electron density, we can further constrain the integrated magnetic field. By assuming from Figure 4 that the DM contribution on 23 December is approximately $0.04 \text{ cm}^{-3} \text{ pc}$ for the line of sight to J1801-2304 our RM measurement constrains the net integrated line-of-sight magnetic field to be approximately $0.5 \text{ } \mu\text{T}$ at an elongation of 0.96° from the centre of the disc (2.7 solar radii from the solar limb).

4. Conclusion

We have presented details of an experiment with the potential to independently probe both the electron and magnetic field properties within the solar corona. We have proven the practicality of this experiment by presenting rotation measure variations detected as PSR J1801-2304 passed close to the limb of the Sun. These RM measurements indicate a net magnetic field of $0.5 \mu\text{T}$ at 2.7 solar radii from the solar limb.

This experiment, if conducted in a more complete manner, has the potential to independently map the coronal plasma density and magnetic field along multiple lines of sight. As such it is a useful contribution to the current experimental probes of coronal properties.

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