First Ever Measurement of Quiet Sun Magnetic Field at Higher Coronal Heights Using Spectro-Polarimetric Radio Observation with SKA Precursor

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Abstract

Magnetic field couples the solar interior to the solar atmosphere, known as the corona. The coronal magnetic field is one of the crucial parameters which determines the coronal structures and regulates the space weather phenomena. Measuring the magnetic field at middle and higher coronal heights is an extremely difficult problem. It is particularly more challenging for the quiet solar corona, where the magnetic field strength is small. To date, there is no single measurement technique available to measure the quiet coronal magnetic field at middle and higher coronal magnetic fields. Theoretically, it is possible to measure the quiet Sun coronal magnetic field using very small (< 1 %)induced circular polarization of thermal emission at low radio frequencies, which is not detected to date. With the newly developed precise polarization calibration of the solar observations done with the Murchison Widefield Array, a future Square Kilometer Array (SKA) precursor, we have brought down the instrumental polarization < 1 %. This precise calibration allows us to detect the induced circular polarization from the quiet Sun for the first time. We have measured the magnetic field strength of the quiet solar corona using this method. We anticipate this method will provide good constraints to the different magnetic field extrapolation methods used largely for coronal magnetic field estimation.

1 Introduction

Solar corona is the outermost layer of the Sun and is made up of hot magnetized plasma. The magnetic field permeating this plasma couples the solar atmosphere to the solar interior. Solar magnetic fields are responsible for the bulk of the observed solar phenomenon, spanning a range of time scales from solar cycle to flares lasting milliseconds and in terms of the energy from massive coronal mass ejections (CMEs) to nanoflares. Hence, to understand coronal dynamics it is essential to measure and understand the ever-evolving coronal magnetic fields. The sun and the corona are routinely observed using multiple space and ground-based instruments, spanning the range from radio to X-ray wavelengths. Magnetic fields, however, are rather hard to measure, and the observations at infrared wavelengths can provide routine estimates of magnetic fields at low coronal heights (1). Under favorable circumstances, radio observations have also been used to estimate coronal magnetic fields associated with active regions and/or CMEs (2). Most of the radio studies have focused on the active emissions, and the global quiescent coronal magnetic fields at high coronal heights have remained beyond reach. Hence for quiet coronal magnetic fields are estimated using different extrapolation techniques (3; 4; 5).

To understand the evolution of the large-scale magnetic field of the quiet Sun, one has to measure the magnetic field over a small time scale. Polarization measurements of the induced circular polarization of the quiet Sun thermal emission can be used to measure the global coronal magnetic field over much larger coronal heights (6) routinely using small temporal integration. Despite its well-appreciated importance, these measurements have not been possible due to technical and instrumental limitations. These limitations have been overcome using a new generation instrument, the Murchison Widefield Array (MWA) (7), operating at 80 – 300 MHz. This along with a robust polarization calibration and imaging pipeline, called “Polarimetry using Automated Imaging Routine for the Compact Arrays for the Radio Sun" (P-AIRCARS) (8), allows us to make full Stokes solar images with high-fidelity and high-dynamic-range.

In this paper, we present the first detection of induced circularly polarized emission from thermal emission of the quiet Sun. The rest of the paper describes the theoretical expectations (Section 2), the effect of propagation on the estimated magnetic field, and a simple method to estimate the quiet coronal magnetic field using the detected circular polarization.

2 Theoretical Predictions

At radio wavelength, the induced circular polarization of the quiet Sun thermal emission can be used to measure the large-scale global coronal magnetic field (6). Thermal bremsstrahlung emission is intrinsically un-polarized. While it propagates through the birefringent magnetized coronal plasma, the ordinary (O-mode) and extra-ordinary

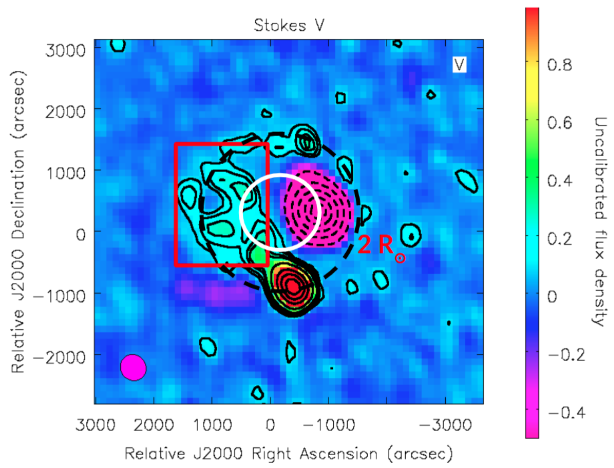

Figure 1. First ever detection of induced circular polarization from the quiet Sun thermal emission. Circular polarisation images at 96 MHz are shown. The images are made over 160 kHz spectral and 0.5 s of temporal integration. The inner white circle represents the optical disk of the Sun. *Top panel :* This is a circular polarization image. The red box shows the quiet Sun region. *Bottom panel :*This shows the circular polarization fraction image. The average circular polarization faction over the quiet Sun region is about 0.5 %.

(X-mode) polarization components of the thermal emissions are absorbed differentially. This differential absorption produces circular polarization with polarization fraction, r_c (9):

$$r_c = \frac{T_{b,X} - T_{b,O}}{T_{b,X} + T_{b,O}} \tag{1}$$

where, $T_{b,X}$ and $T_{b,O}$ are the brightness temperature of X- and O-mode polarization.

The value of r_c depends on the line of sight magnetic field of the solar corona. Hence, if one can measure the r_c, it can be reverted to measure the line of sight integrated magnetic field strength at middle and higher coronal heights. According to the theoretical prediction, (6), the expected circular polarization is $\approx 0.5 - 0.8$ %, for an average quiet Sun photospheric magnetic field of 0.5 G, which can be detected with very precise polarization calibration.

3 First Detection of Circular Polarization from Quiet Sun

Using P-AIRCARS we have successfully detected the circularly polarized emission from quiet Sun thermal emission for the first time. Figure 1 shows the first-ever detection of circular polarization from quiet Sun. The left panel is the circular polarization images in calibrated flux density. The white circle represents the optical disk of the Sun and the black dotted circle represents the 2 $R_\odot$. The image is made at 96 MHz and only over 160 kHz spectral and 0.5 s temporal integration. The quiet Sun region is chosen with $T_B \leq 10^6$ K and marked by the red square box in the left panel of Figure 1. We have detected circularly polarized emission over a significant region with more than 7σ detection significance. The right panel shows the circular polarization fraction image of the same observation. The average circular polarization over the quiet Sun region is ~ 0.5 %, and the residual instrumental leakage is < 0.07 %. This extremely small residual instrumental leakage makes the fidelity of this detection high.

4 Propagation Effects in Corona

At low radio frequencies, there are two major propagation effects – refraction and scattering. The presence of the magnetic field in the corona makes it an-isotropic and in-homogeneous. The refractive index in the in-homogeneous corona at low frequencies varies from zero to unity. Hence, the ray paths are not straight in the corona. To estimate the absorption of both the X- and O-mode accurately, one has to find the ray path along which the energy propagates and has to integrate the absorption coefficients along that ray path.

We have used the Haselgrove equations (10; 11; 12) to determine the ray path in the corona. Haselgrove equations are ordinary differential equations in two dimensions. There are two magneto-ionic quantities in Haselgrove equations (6), which are directly related to the coronal electron density and magnetic field. These two quantities are:

1. $X = \frac{\nu_p^2}{\nu^2}$, where ν_p is the plasma frequency, and ν is the observing frequency. Under the cold plasma assumption, ν_p is proportional to the $\sqrt{n_e}$, where n_e is the local electron density.

2. $\vec{Y}$ is a vector parallel to the magnetic field and its length is equal to the magneto-ionic parameter; $Y = \frac{\nu_{ce}}{\nu}$, where, ν_{ce} is the electron gyro-frequency, which depends on the magnetic field strength.

This dependency of the optical depth on electron density and magnetic field distribution allows estimating both the coronal electron density distribution and magnetic field distribution based on some free parameter models. Coronal electron density distributions were estimated previously by the multi-frequency quiet Sun observations at low radio frequencies using Nançy Radioheliograph (13) and LOFAR (14). One can solve Haselgrove equations for different realizations of free parameters and fit the observed circular polarisation to constrain these free parameters of the magnetic field model and estimate the magnetic field at any coronal heights using this magnetic field model constraint by observations.

In this work, we have only considered the effects of refraction into account. At low radio frequencies, another major effect is scattering. Corona density inhomogeneities cause

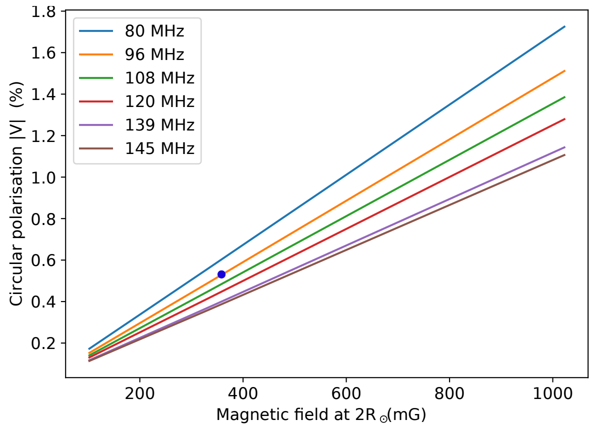

Figure 2. Variation of circular polarization fraction against the LoS averaged magnetic field strength at 2 $R_{\odot}$. Variations for different frequencies are shown in different colours. Circular polarization fraction increases with the magnetic field, and at the low frequencies. The blue dot corresponds to the averaged circular polarization fraction of 0.5 % at 96 MHz. Corresponding LoS magnetic field strength at 2 $R_{\odot}$ is about 380 mG.

the scattering of the radio emission. Scattering is a non-linear process. Its effect can be determined statistically, but the exact inversion of the scattering effect is a challenging problem. The effect of scattering on type-III radio bursts (15) and quiet Sun emissions (16) has been studied recently. But, the effect of scattering on the measured circular polarization fraction from quiet Sun thermal emission has not been studied in detail, which is out of the scope of this paper.

5 Estimated Quiet Sun Coronal Magnetic Field

For simplicity, in this work, we have assumed Newkirk coronal density model (17), and a very simple radial magnetic field model; $B_\mathrm{r} = B_0(\frac{R}{R_\odot})^{-2.29}$ (18) . We have solved the Haselgrove equations in two dimensions and obtained the circular polarization fraction at different observing frequencies for different LoS averaged magnetic field strengths. Variation of circular polarization fraction against the LoS averaged magnetic field strength at 2 $R_{\odot}$ is shown in Figure 2. We have detected an average circular polarization fraction of 0.5 % at 96 MHz. Blue dot in Figure 2 shows the observed circular polarization fraction at 96 MHz. Corresponding estimated LoS averaged magnetic field strength at 2 $R_{\odot}$ is about 380 mG.

6 Conclusion

Magnetic field measurements at coronal heights are extremely challenging. One of the ideal methods known is the circular polarization measurements of the quiet Sun thermal emission. At the same time, it is also known that the induced circular polarization of thermal emission for the quiet Sun is extremely small. But, due to technical and instrumental limitations, there was not a single measurement of the induced circular polarization from quiet Sun thermal emission. With very precise polarization calibration and new technology instruments, like the MWA, we have detected the induced circular polarization from quiet Sun thermal emission for the first time. To verify our detection with theoretical expectations (6), we have estimated the magnetic field strength considering only the refraction. We find the estimated LoS magnetic field strength comes out as 380 mG, which is a similar order of magnitude as predicted by several extrapolation methods.

The radial magnetic field model used in this work does not represent the true magnetic field of the corona. In the future, we will incorporate a more realistic parameterized magnetic field model and fit the free parameters of the model using multi-frequency polarimetric observation of quiet Sun circular polarization. We also need to study the effects of scattering on the measured polarization fraction and estimate the level of uncertainty it introduces in the magnetic field measurements. Although there is still a lot of work to do to extract the accurate magnetic field strength of the solar coronal at higher heliocentric heights, this first detection allows the community to explore this in detail, which was not explored in detail due to the unavailability of the detection. This work is a first step towards using the spectro-polarimetric radio observation of quiet Sun for coronal magnetography.

7 Acknowledgements

This scientific work makes use of the Murchison Radio-astronomy Observatory (MRO), operated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site. Support for the operation of the MWA is provided by the Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS), under a contract to Curtin University administered by Astronomy Australia Limited. We acknowledge the Pawsey Supercomputing Centre, which is supported by the Western Australian and Australian Governments. We acknowledge support of the Department of Atomic Energy, Government of India, under the project no. 12-R&D-TFR-5.02-0700. SM acknowledges partial support by USA NSF grant AGS-1654382 to the New Jersey Institute of Technology. We thank the developers of Python (19) and the various associated packages, especially Matplotlib (20), Astropy (21) and NumPy (22).

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