Reduced Microwave Brightness Temperature in a Sunspot Atmosphere Due to Open Magnetic Fields

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Abstract
Motivated by dark coronal lanes in 284 Å extreme-ultraviolet (EUV) observations from the Extreme-ultraviolet Imaging Telescope on board the Solar and Heliospheric Observatory (SOHO/EIT), we construct and optimize an atmosphere model of the active region (AR) 8535 sunspot by adding a cool and dense component in the volume of plasma along open field lines determined using the potential-field source-surface (PFSS) extrapolation. Our model qualitatively reproduces the observed reduced microwave brightness temperature in the northern part of the sunspot in Very Large Array (VLA) observations from 13 May 1999 and provides a physical explanation for the coronal dark lanes. We propose the application of this method to other sunspots with such observed dark regions in the EUV or soft X-rays and with concurrent microwave observations to determine the significance of open field regions. The connection between open fields and the resulting plasma temperature and density change is of relevance for slow solar wind source investigations.

1. Introduction

No scientific consensus exists on an effective solar atmosphere model (see Loukitcheva et al., 2017, for an overview). This issue is relevant to solve the well-known coronal heating problem. Active region (AR) sunspot observations at microwave wavelengths can be used for solar atmosphere density and temperature profile investigations. In this paper, for the AR 8535 sunspot, we further relate an observed local decrease in microwave intensity to open field lines and thereby demonstrate the additional contribution of high angular resolution microwave observations to magnetic field connectivity determination.

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A significant contribution to the microwave radiation from large sunspots comes from the gyroresonance emission by electrons in the strong (compared to surrounding quiet Sun) sunspot magnetic fields. Two features make this emission of particular use in investigating the active region atmosphere: (1) the emitted radiation is in local thermodynamic equilibrium (LTE) with the plasma, and hence the brightness temperature derived from the observed electromagnetic radiation flux in the cases of sufficient optical depth represents the actual local electron temperature (averaged over a resolution element), and (2) for gyroresonance emission, the plasma has a significant optical depth only in thin layers where the emission frequency is close to the gyrofrequency or its harmonics. As a result, gyroresonance emission brightness temperature observations represent the plasma temperature at selected heights in the atmosphere. A successful “inversion” of the microwave observations could then provide information on the atmospheric structure and the magnetic field of sunspots.

Since the realization of the relevance of the gyroresonance emission mechanism to the observed microwave emission from sunspots (Zheleznyakov, 1962; Kakinuma and Swarup, 1962), numerous attempts with varying success have been made in investigating active regions using such observations (for a review, see Gary and Keller, 2004; Lee, 2007). Arguably, the most straightforward approach is to use a model for the sunspot magnetic field (based on either a photospheric magnetic field extrapolation or a dipole model) together with an assumed atmosphere model (density and temperature, usually plane-parallel) to calculate the microwave emission, which is then compared to observations. Such approaches can be successful for sufficiently simple sunspots, yet numerous exceptions exist.

In some cases, authors concluded that the field above the sunspot is not a potential field (Alissandrakis, Kundu, and Lantos, 1980; Nindos et al., 1996; Brosius et al., 2002), and a more involved magnetic field model was necessary.

In other cases, it was suggested that a layer of low-temperature plasma overlies some parts of the sunspot. In particular, several authors (Alissandrakis and Kundu, 1982; Strong, Alissandrakis, and Kundu, 1984; White, Kundu, and Gopalswamy, 1991; Zlotnik, Kundu, and White, 1996; Zlotnik, White, and Kundu, 1998; Bezrukov et al., 2011; Bezrukov, Ryabov, and Shibasaki, 2012) invoked low-temperature plasma above the center of the sunspot and at the relevant gyroresonance levels to explain the fact that the observed reduction in emission is more pronounced than would be expected solely due to the small angle between the magnetic field and the line of sight there. Previously, cool plasma in the corona over several sunspots had been observed in EUV (Foukal et al., 1974; Foukal, 1981). Brosius and White (2004) directly observed both enhanced transition region EUV emission (“sunspot plume”) and reduced microwave emission at the same location in an AR in coordinated EUV and microwave observations with the Coronal Diagnostic Spectrometer (CDS) on board the Solar and Heliospheric Observatory (SOHO) and the Very Large Array (VLA), respectively.

First, Gary and Hurford (1994) and, most recently, Tun, Gary, and Georgoulis (2011) analyzed spatially resolved microwave spectra of active regions without relying on any magnetic field models and discovered locations where the radio spectra exhibit positive slopes – higher brightness temperatures at higher frequencies – which, again, implies lower-temperature plasma higher in the solar corona than the underlying high-temperature plasma. An important distinction is that in these cases the cool plasma is in loops high in the corona and not necessarily at the relevant gyroresonance levels.

Finally, Vourlidas, Bastian, and Aschwanden (1997) explained microwave observations using a model that encompassed both concepts, lower-temperature plasma at certain gyroresonance layers and constrained to lie in particular loops.

For completeness, we should mention that observations in other parts of the electromagnetic spectrum, optical and UV spectral lines, are also used to construct sunspot atmosphere
models. The “inversion” at these wavelengths is more complicated since the radiative transfer is then a non-LTE process and the emission depends on the abundance and ionization equilibrium of particular atoms. Nevertheless, numerous models have been constructed, and we refer to Loukitcheva et al. (2017) for an overview of the models and their correspondence to radio observations.

Despite the aforementioned advances, research on sunspot atmosphere modeling using microwave observations continues. Goals include better agreement between models and observations and justification or elimination of model assumptions. Thus, more recently, Stupishin et al. (2018) iteratively varied a plane-parallel atmosphere profile to use with a nonlinear force-free (NLFF) reconstructed magnetic field to model the Radio Astronomical Telescope of the Academy of Sciences-600 (RATAN-600 in Russian) 1D sunspot observations. Also for modeling RATAN-600 observations, Alissandrakis et al. (2019) in turn employed an inversion of the differential emission measure from the Atmospheric Imaging Assembly (AIA) observations on board the Solar Dynamics Observatory (SDO) to obtain the atmosphere profile to be used together with potential field extrapolations.

As for a physics-based justification of the empirical models, Lee et al. (1998) set different temperature profiles for plasma along different magnetic field lines, chosen based on the current along the given field line derived from an NLFF magnetic model. More recently, Mok et al. (2016) modeled volumetric plasma heating in an active region as dependent on magnetic field strength, length of field lines, and plasma density. However, these authors simulated and compared to observations the emission in the EUV rather than at radio wavelengths.

Fleishman et al. (2021), using the IDL-based software package GX_Simulator in SolarSoft developed by Nita et al. (2018), performed similar modeling but using quantitative comparisons with observations of microwave emission at 17 GHz. The authors investigated the sufficiently complex AR 11520 with observed areas of both optically thick and optically thin gyroresonance emission, which allowed for constraining the proposed coronal heating law. However, for this AR, neither the observations nor the modeling suggests the existence of cool overlying plasma.

In this article, we focus on the sunspot of AR 8535 observed on 13 May 1999 using the VLA. This particular large sunspot exhibits features in microwave observations that cannot be reproduced with a simple, that is, plane-parallel, atmosphere model. In particular, the microwave emission is reduced in the northern part of the sunspot, and there is an inversion in brightness temperature with respect to frequency in several regions, which are brighter in the 8 GHz band than in the 5 GHz band. As already described, this is suggestive of cool plasma overlying hotter lower layers; such an interpretation for this spot was suggested and investigated by Brosius and White (2004), who associated the depression with a sunspot plume detected in coordinated EUV observations with SOHO/CDS. This particular plume was further described by Brosius and Landi (2005). Note that these authors refer to this active region as AR 8539.

Ryabov and Shibasaki (2016) investigated this same sunspot in the microwave, EUV, and X-ray ranges and argued that the observed reduced brightness in microwaves, dark lanes in EUV and X-ray images, regions of open field lines, and regions of outflows all overlap and are related. Their interpretation was that hot coronal plasma had been evacuated along the open field lines leaving a volume of cooler plasma, which is seen as a depression in the microwave observations. Their work extends the previous work by Ryabov et al. (2015), who used similar arguments to explain the reduced microwave brightness at 17 GHz in the peripheral areas of five other selected sunspots.
Our goal in this work is to model the sunspot atmosphere containing such low-temperature plasma along open field lines to obtain an agreement with microwave observations. Plasma outflow along open field lines then would have significant observational consequences and would be a physical mechanism to include in justifying empirical models.

Whereas information on the atmosphere and magnetic fields of active regions is of interest in itself, our hypothesis is of additional significance since it implies that active regions contain open field regions that can act as sources of the slow solar wind with observational signatures in microwaves. The rich surrounding coronal magnetic field structure of the AR 8535 sunspot is investigated in detail by Ryabov and Vrublevskis (2020) with evidence presented from solar wind modeling and measurements in favor of outflows. The reader is referred to Abbo et al. (2016) for a comprehensive review of observations and current theories regarding sources of the slow solar wind.

This paper is organized as follows. In Section 2, we present the observations followed by a description of our modeling of the sunspot atmosphere to match microwave data in Section 3. We then draw conclusions and discuss the results in Section 4.

2. Observations

NOAA AR 8535 was observed on 13 May 1999 with multiple instruments. The active region included a positive polarity sunspot, which is the object of the present investigation. During the observations the sunspot was located to the northwest of the disk center. Overview data from the Michelson Doppler Imager (MDI) instrument (Scherrer et al., 1995) at 24:00 UT and the EIT instrument (Delaboudinière et al., 1995) at 19:06 UT (both on board the SOHO satellite) are presented in Figure 1.

In panel a, we show the white light image from the MDI instrument. We use it to mark the sunspot umbra and penumbra. The corresponding contours are then overlaid for reference in panel b and in the following figures. Contours from the MDI white light data at 19:06 UT (not shown) were used in panel c.

Panel b displays the measured photospheric longitudinal magnetic field. The maximum value is 2760 G, which is sufficient for relevant gyroresonance harmonic layers to be present in the sunspot atmosphere.

Panel c contains an EUV image at 284 Å obtained with the EIT. Of particular interest is the dark region emanating northward from the sunspot, suggesting the absence of hot coronal plasma on those field lines.

It is important that this sunspot was also observed using the VLA between 20:00 and 24:00 UT. Observations at three frequencies, 4.535, 8.065, and 14.665 GHz, and in both right and left circular polarizations (RCP and LCP, respectively) are presented in Figure 2, where the microwave brightness temperature is plotted. The same constant offsets as in Brosius and White (2004), $1.67 \times 10^4$, $1.26 \times 10^4$, and $1.14 \times 10^4$ at the three frequencies, respectively, were added to the measured brightness temperatures to account for the expected quiet-Sun brightness temperature background, which interferometrically is not measured. Since the sunspot is of positive polarity, the right and left circular polarizations predominantly correspond respectively to the extraordinary and ordinary modes of microwave emission. With the VLA in the “D” configuration, the spatial resolutions (beam widths) in the images at the three frequencies are 15″, 10″, and 5″, respectively. Note the different color bar scale for the 15 GHz data. The RCP images in panels a–c are clipped, and the actual measured brightness temperatures reach 3.2, 3.3, and 1.6 MK, respectively (see Section 3.1). For better alignment with model data, which are based on MDI magnetic field measurements from 24:00 UT, the VLA data have been shifted 33.4″ to the west and 2.0″ to the south.
Figure 1 AR 8535 observed on 13 May 1999. (a) MDI white light image and (b) MDI photospheric longitudinal magnetic field measurements taken at 24:00 UT. (c) EUV 284 Å image from EIT at 19:06 UT. Contours of the sunspot umbra and penumbra are overlaid in panels b and c.

Figure 2 Brightness temperatures of AR 8535 measured on 13 May 1999 with the VLA at three frequencies in both right and left circular polarizations (RCP and LCP, respectively). The dashed line in panel d shows the cross-section used in quantitative comparisons with model results. The cross in panel d marks the location that is further analyzed in the text where the RCP brightness temperature is greater in 8 GHz than in 5 GHz. Overlaid are the contours of the sunspot umbra and penumbra.

3. Modeling of the Microwave Observations

3.1. Model Setup

From Figure 2 we can note the following peculiar observational features that justify the proposed model:
I. The sunspot displays an irregular shape in the microwave data. Most clearly in the 8 GHz RCP measurements, three bright areas can be distinguished, which are evident in the 5 GHz data as well. The sunspot is particularly irregular in the 15 GHz RCP data, where a 1.6 MK bright spot exists to the north–east of the sunspot center, whereas the brightness temperature is less than 0.3 MK in the rest of the sunspot.

II. A pronounced region of reduced brightness temperature can be observed in the northern part of the sunspot, around (360′′, 400′′), in the 5 and 8 GHz RCP data.

III. Four areas exist where the sunspot brightness temperature in the RCP (i.e., in the predominantly extraordinary mode) at 8 GHz exceeds the brightness temperature at 5 GHz (blue in Figure 10a). Three of these areas correspond to the bright areas described as part of feature I above. The fourth area near (360′′, 396′′) (location marked with a cross in Figure 2d) is within the reduced brightness temperature area that is feature II.

We first focus on the three bright areas from features I and III. The higher brightness temperature at 8 GHz than at 5 GHz is unusual since in a typical sunspot the 5 GHz optically thick gyroresonance layers would lie higher in the atmosphere, where we expect higher electron temperature than at the corresponding 8 GHz gyroresonance layers. As was already pointed out in the Introduction, one possible explanation as invoked by Gary and Hurford (1994) and more recently by Tun, Gary, and Georgoulis (2011) is that cool coronal loops overlie these areas at heights above the relevant gyroresonance layers. Since the optical depth for free–free absorption by a given cool loop plasma volume is inversely proportional to the square of the frequency, 5 GHz emission from lower and hotter layers would be absorbed more than the 8 GHz emission. However, it would then require a special coincidence that this high cool plasma from feature III overlies exactly the areas from feature I that are of significantly higher brightness temperatures than other areas of the sunspot.

An alternative explanation adopted here is that at the locations of the bright areas in feature I, the plasma in a given flux tube is actually cooler in the higher 5 GHz optically thick gyroresonance layers than in the lower 8 GHz gyroresonance layers. This is distinct from a model where the emission at the two frequencies arises in different flux tubes along the same line of sight. We adopt this explanation without explicitly establishing the cause for this temperature inversion along the flux tube. The apparent sizes of the bright areas are comparable to the beam widths at these frequencies. Thus although it cannot be determined with certainty, the locations of the bright areas in the images at different frequencies, radially more outward from the sunspot center with decreasing frequency, are consistent with an interpretation that each bright area represents a flux tube that is observed at different heights in different frequencies. Presumably then due to some undefined process, plasma is of an increased electron temperature relative to its surroundings along three flux tubes (feature I), but with greater temperature at the lower heights of the 8 GHz gyroresonance layers (feature III). Our goal is to model the sunspot atmosphere outside these flux tubes, presumably unperturbed by this process.

Feature II is also unusual. The optical depth of gyroresonance emission depends strongly on the angle between the magnetic field and the line of sight and approaches zero as this angle is decreased (i.e., looking along the field line). Thus for a sunspot with a symmetric magnetic field, a decrease in brightness temperature is expected closer to disk center, which in our case is to the southeast from the sunspot center. The opposite is observed here: the decreased brightness temperature is to the northwest of the sunspot center.

Inspired by the EUV observations (Figure 1c), similar soft X-ray observations (not shown), and previous work by Ryabov et al. (2015) and Ryabov and Shibasaki (2016), we pose the hypothesis that open magnetic field lines are present in the northern part of
the sunspot. Due to increased plasma transport along these open field lines, we could then expect reduced amounts of hot coronal plasma in the corresponding volume.

To model such a case, we constructed a model atmosphere centered on our sunspot at (360°, 382′′) and consisting of $41 \times 41 \times 2401$ rectangular cuboid voxels with horizontal spacing of 1432 km (equivalent to 1.9638″ or 0.002058 R$_{\odot}$) and vertical spacing of 117 km (equivalent to 0.000168 R$_{\odot}$). In the vertical direction (Z-axis) the volume is along the line of sight. We aligned the X-axis with the heliocentric west direction and the Y-axis with the heliocentric north direction.

### 3.2. Magnetic Field Model

We use the potential-field source-surface (PFSS) extrapolation of the measured surface magnetic field (Altschuler and Newkirk, 1969; Schatten, Wilcox, and Ness, 1969) to specify the magnetic field at each voxel.

The PFSS extrapolation assumes that the magnetic field is completely radial at a “source surface” at some radius $R_{SS}$, which is a model parameter traditionally set at $R_{SS} = 2.5$ R$_{\odot}$. However, other values of this parameter have been used to better match observations. Lee et al. (2011) obtained better agreement with observations with $R_{SS} \approx 1.9$ R$_{\odot}$ and $R_{SS} \approx 1.8$ R$_{\odot}$ for the minimum periods of Cycles 22 and 23, respectively. More recently, Bale et al. (2019) used $R_{SS}$ as low as 1.2 R$_{\odot}$ to reproduce some of the magnetic field features observed in situ by the Parker Solar Probe at 36 to 54 solar radii in October–November 2018. A lower source-surface increases the volume of the atmosphere with open field lines. With that in mind, below, we focus on PFSS extrapolations and the resulting atmosphere models with $R_{SS} = 1.8$ R$_{\odot}$, exploring the $R_{SS} = 2.5$ R$_{\odot}$ case afterward.

Since the reduced brightness region (feature II) that we claim to be caused by open field lines is of 0.5 heliospheric degree characteristic size, a high-resolution magnetic field reconstruction is necessary to model and trace magnetic field lines in our model atmosphere. At the same time, a global model is necessary to accurately identify field lines as open or closed. We achieve these two goals by following these steps:

i) We start with the precalculated $384 \times 192$ data point global surface radial magnetic field map (Schrijver and DeRosa, 2003) from the Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), which is based on 6-hour cadence observations at 00:04 UT on 14 May 1999. We interpolate the field to a finer $3874 \times 1937$ data point grid, which is roughly double the spatial resolution of the 96-min cadence full-disk MDI longitudinal magnetic field measurements.

ii) We use such 96-min cadence longitudinal field measurements from 24:00 UT on 13 May 1999 (see Figure 1b) and calculate the radial magnetic field for $161 \times 161$ data points on the disk corresponding to the area between 242″ and 557″ along the X-axis and between 264″ and 579″ along the Y-axis. This high-resolution radial field is likewise interpolated to the grid from step i and is used as a substitution for the lower-resolution radial field data near our sunspot.

iii) We perform the PFSS extrapolation using appropriately modified routines from the pfss package (Schrijver and DeRosa, 2003) in SolarSoft. The magnetic field is calculated on a grid in spherical coordinates with uniform $\pi / 1937 = 0.00162$ rad spacing in angular coordinates and the same 117 km (equivalent to 0.000168 R$_{\odot}$) spacing in the radial coordinate, for a volume that encompasses the atmospheric region of interest. Crucially, the number of spherical harmonics used is kept large to ensure a high-resolution magnetic field reconstruction. In particular, we implement the same somewhat arbitrary limit, provided in the SolarSoft pfss package routines, that the number of spherical
harmonics $\ell$ used for reconstructing the field at a radial coordinate $r$ (expressed in $R_\odot$) is such that $r^{\ell} < 10^6$ and no larger than 1937.

iv) We use a trilinear interpolation to obtain magnetic field values for the model atmosphere volume. Here we assume that due to the fine coordinate spacing compared to the curvature radius, for interpolation purposes, each voxel in spherical coordinates can be approximated as rectilinear.

v) For the global field calculations, we use the default routines and the grid from the LSM-SAL precalculated fields, only with extrapolations performed using our modified surface radial magnetic field map and with our chosen $R_{SS}$ values.

Since the observed gyroresonance emission is strongly dependent on the angle between the magnetic field and the observer, in explaining the reduced microwave brightness temperature (feature II), we must differentiate between the effects of the proposed cool plasma and the influence of any smaller scale field irregularities in which the field is aligned closer to the line of sight than expected for a regular sunspot. To address this issue, in Figure 3b, for the atmosphere model volume, we have plotted the magnetic field magnitude at a relevant height of 1400 km with contours (going inward) for the relevant harmonics (with the harmonic number indexed with s): 540 G for 5 GHz $s = 3$, 810 G for 5 GHz $s = 2$, 960 G for 8 GHz $s = 3$, and 1441 G for 8 GHz $s = 2$. The contours are to a great extent symmetric, suggesting that any magnetic field irregularities present are insufficient for the magnetic field structure alone to account for the decreased brightness temperature in the northern part of the sunspot.

The general existence of open field lines can be demonstrated by tracing representative field lines from the surface in the global magnetic field model, as shown in Figure 3a, where the green field lines are open, whereas the black ones are closed. To identify, using the global model, voxels in our atmosphere model volume that lie on open magnetic field lines, we first
choose a reference height in the volume, where we relate the high-resolution atmosphere model field connectivity to the global model field connectivity. We choose 90 Mm above the sunspot center. Then for each voxel in the model volume, we trace a field line starting from that voxel and determine the pixel (if any) at the reference height that the field line intersects. For the global model, we trace field lines from coordinates corresponding to each of the pixels at the reference height and determine if the field line is open or closed. Then all the voxels that are magnetically connected to the reference height pixels in the atmosphere model volume, which are in turn determined to lie on open field lines in the global model, are considered to also lie on open field lines.

For magnetic field line tracing purposes, we used a model volume extended westward and northward to $81 \times 81 \times 2401$ pixels to properly identify as open field lines those that leave the nominal atmosphere model volume.

Overall, we divide all the atmosphere model volume into two subvolumes or components. One, the open field component, corresponds to the voxels lying along open field lines. The other, the bulk component, corresponds to the rest of the volume. We can envision distinguishing additional components to model the flux tubes corresponding to the bright areas in the VLA data. The open field component is shown in Figures 4a and 4b from different viewpoints with respect to the atmosphere model volume, the Sun surface, and the sunspot. Note that the Z-axis (vertical) is not to scale in Figure 4a. In Figure 4c the borders of the open field component at different heights along the Z-axis are shown. Near the surface of the Sun at $Z = 40$ Mm, the border of the open field component (solid line in Figure 4c) is in the northern part of the sunspot atmosphere and is remarkably coincident with the region of reduced brightness temperature (feature II) in the microwave observations (see Figures 2a and 2b). The open field lines initially continue northward, and the open field component occupies only the northern part of the model volume at $Z = 120$ Mm (dash-dotted line in Figure 4c). With increasing height, the open field lines spread out, and eventually a signifi-
cant portion continues southward across the model volume. At $Z = 200 \text{ Mm}$ the open field component occupies already half of the model volume cross-section.

### 3.3. Atmosphere Model

Having established the open- and closed-field subvolumes, we then set atmosphere parameters, electron temperature and density, as functions of height $h$ above the Sun’s surface for each of the components. We use the model of Alissandrakis, Kundu, and Lantos (1980) that parameterizes the atmosphere above the chosen transition temperature of $T_0 = 100 \times 10^4 \text{ K}$ using three parameters: (1) height $h_0$ for this transition temperature, (2) pressure at this transition point, and (3) conductive heat flux $F_C$ in the atmosphere above the transition point. For convenience in our case, we vary the related quantity, electron density $n_0$, instead of pressure. Above the transition height the temperature increase is assumed to correspond to a constant conductive heat flux $F_C$, whereas for the density, we assume hydrostatic equilibrium and ignore the variation of specific gravity with height. We allow the temperature to increase up to a maximum coronal temperature $T_{\text{COR}} = 8 \times 10^6 \text{ K}$. The exact upper limit is not important since the corona becomes optically thin at these heights and no longer contributes significantly.

Quantitatively, in cgs units, we then have (Alissandrakis, Kundu, and Lantos, 1980)

$$T(h) = \left[ T_0^{7/2} + \frac{7}{2} F_C A(t(h) - h_0) \right]^{2/7}, \quad \text{(1)}$$

and

$$n(h) = n_0 \left( \frac{1}{t(h)} \right) \exp \left[ -\frac{8.91 \times 10^{-11} \times T_0^{5/2}}{F_C} \left( t(h)^{5/2} - 1 \right) \right], \quad \text{(2)}$$

where $A = 1.1 \times 10^{-6} \text{ erg cm}^{-1} \text{ s}^{-1} \text{ K}^{-7/2}$, and $t(h) = T(h)/T_0$. At heights below $h_0$, we assume a constant temperature of $5000 \text{ K}$ and density of $10^{11} \text{ cm}^{-3}$.

With magnetic field, plasma temperature, and density defined in the model volume, we can calculate the expected brightness temperature at the three observing frequencies. We invoke two emission mechanisms, thermal gyroresonance and free–free emission (i.e., thermal bremsstrahlung). We adapted the code from the FORWARD package (Gibson et al., 2016) in SolarSoft. The opacity $\kappa$ at frequency $f$ due to free–free emission is calculated approximately according to the simplified formula (Dulk, 1985; Gelfreikh, 2004)

$$\kappa = 0.2 \frac{n^2}{T^{3/2} (f \pm f_B |\cos \theta|)^2}, \quad \text{(3)}$$

where $f_B$ is the gyrofrequency at the given voxel location, and $\theta$ is the angle between the magnetic field direction and the line of sight. The plus sign is for the ordinary mode, and the minus for the extraordinary one. From the opacity we can calculate the optical depth $d\tau$ due to a layer of geometrical depth $ds$ according to

$$d\tau = \kappa \ ds. \quad \text{(4)}$$

For thermal gyroresonance instead, the optical depth due to a gyroresonance layer is directly calculated for voxels where these layers are crossed. In the FORWARD package, this is done using the approximations from Robinson and Melrose (1984). Effectively, then within our
model the width of all gyroresonance layers is 117 km. Note also that we modified the FORWARD routines, and for the magnetic field scale length estimate, we used the derivative along the line of sight of the more correct magnetic field magnitude $B$ rather than of the component of the field along the line of sight $B_z$: $L_B = B \times |dB/dz|^{-1}$ instead of $L_B = B_z \times |dB_z/dz|^{-1}$.

The total optical depth at the given frequency for the given voxel is the sum of the optical depths due to both mechanisms. Knowing the optical depth, we integrated the radiative transfer equation along each of the $41 \times 41$ vertical columns within the atmosphere model volume. Passing through each voxel, some of the incident radiation with brightness temperature $T_B$ is absorbed, whereas some with the voxel electron temperature $T_e$ is emitted, depending on the optical thickness of the layer $d\tau$ according to the formula

$$T_B' = T_B e^{-d\tau} + T_e \left(1 - e^{-d\tau}\right),$$

where $T_B'$ is the brightness temperature of the radiation exiting the given voxel. After calculating the brightness temperatures for each individual column, we then applied Gaussian smoothing to account for the beam widths in the observed data.

For a given atmosphere model, we evaluated the fit to observations by calculating $\chi^2_{\text{pol},f}$ for each polarization and frequency, as well as the combined $\chi^2$, according to the formulas

$$\chi^2_{\text{pol},f} = \frac{1}{T_{\text{pol},f}^{\text{obs}}}_{\text{max}} \sum_i \left(T_{\text{pol},f}^{\text{obs}}(i) - T_{\text{pol},f}^{\text{model}}(i)\right)^2,$$

and

$$\chi^2 = \sum_{\text{pol},f} \chi^2_{\text{pol},f},$$

where $\text{pol}$ stands for either the RCP or the LCP, and $f$ for one of the three observing frequencies. The comparison and the summation are done for image points indexed with $i$, and $T_{\text{pol},f}^{\text{obs}}$ refers to the brightness temperature from observations, whereas $T_{\text{pol},f}^{\text{model}}$ refers to the corresponding value derived from the atmosphere model. For the given frequency and polarization, $\lfloor \text{max} \rfloor$ designates the maximum brightness temperature observed among all the image points indexed with $i$ and used in the comparison.

Since the observed images include bright areas (feature I) that we do not model, for the model fit evaluation, rather than using the complete image, we choose just a cross-section starting south of the sunspot, directed first northward toward the center of the sunspot, and then continuing to the north-west across the region of reduced brightness temperature (feature II). The cross-section is illustrated with a dashed line in Figure 2d. The southern part of the cross-section would correspond to the sunspot atmosphere largely unperturbed by the open field line region, whereas the northern part crosses through the open field. At 5 GHz, we chose a total of 46 points spaced 1.96" apart along the cross-section. To account for the higher spatial resolution in the 8 GHz and 15 GHz observations, the number of points are 69 and 138 with 1.309" and 0.655" spacing, respectively.

In the atmosphere model of Alissandrakis, Kundu, and Lantos (1980) used here, which consists of two components, a total of six parameters would be necessary to specify the temperature and density throughout the volume. However, we assumed that the height $h_0$ of the transition temperature is the same for both model components set by horizontally uniform processes below this height rather than affected by the plasma outflow along the open field.
Table 1  The parameter ranges and the values fitted to the observations for the atmosphere model bulk and open field components.

| Component | Parameter | Value range         | Fitted value |
|-----------|-----------|---------------------|--------------|
| Bulk      | log $n_0$ (cm$^{-3}$) | 8.2–10.2 (increment of 0.4) | 9.4          |
| Bulk      | log $F_C$ (erg cm$^{-2}$ s$^{-1}$) | 5.8–7.4 (increment of 0.4) | 6.2          |
| Bulk      | $h_0$ (km) | 1000–2600 (increment of 200) | 1400         |
| Bulk      | $T_0$ (K) | 100 000 (fixed) | 100 000      |
| Open field| log $n_0$ (cm$^{-3}$) | 8.2–11.0 (increment of 0.4) | 9.8          |
| Open field| log $F_C$ (erg cm$^{-2}$ s$^{-1}$) | 0.0 (fixed) | 0.0          |
| Open field| $h_0$ (km) | (set to the bulk component value) | 1400         |
| Open field| $T_0$ (K) | 80 000–200 000 (increment of 20 000) | 140 000     |

lines in the corona. This is a simplifying assumption since it ignores the Wilson depression. Within our model for the optimized parameters, afterward we checked the impact of varying the height $h_0$ for the open field component and found the effect of the choice to be insignificant.

Qualitatively, the open field component must be modeled with low temperatures in order for the brightness temperatures to be lower than in the bulk component. This requires smaller conductive heat flux values so that the temperature increase with height is more gradual and remains low at the heights effectively sampled by the gyroresonance mechanism. For the density of the open field component, both low and high values can potentially produce the desired effect and must be explored: lower values would lead to lower brightness temperatures through the absence of plasma, whereas higher values would enhance absorption of emission from the hotter lower-lying layers.

We initially calculated a total of 52 000 models. For the bulk component, we explored 10 different $n_0$ values (in cm$^{-3}$, log $n_0$ between 7.4 and 11), 8 $F_C$ values (in erg cm$^{-2}$ s$^{-1}$, log $F_C$ between 5.4 and 8.2), and 10 $h_0$ values between 800 km and 2600 km. For the open field component: 13 different $n_0$ values (in cm$^{-3}$, log $n_0$ between 7.4 and 12.2) and 5 $F_C$ values (in erg cm$^{-2}$ s$^{-1}$, log $F_C$ between 0.0 and 1.6). For these parameters, the best agreement was obtained for log $F_C = 0.0$ for the open field component, which is effectively an isothermal plasma. In this case the exact value of the chosen transition temperature $T_0$ gains additional significance and must be explored.

We thus calculated additional 15 120 models. For the bulk component, we varied parameters near the minimum already found, whereas for the open field component, we fixed log $F_C = 0.0$ and varied $T_0$ between eight different values from 80 000 to 200 000 K. The explored and fitted parameter values are listed in Table 1.

In Figure 5a the model atmosphere temperatures and densities as functions of height for the bulk and open field components using the fitted parameter values are plotted, whereas in Figures 5b and 5c, respectively, the temperature and density along the cross-section used in the fitting are shown. The section is not along a straight line (see Figure 2d), and the location where the direction of the cut changes is shown with a vertical dashed line at Y = 384′′. The Z-axis is not to scale. The contours in black represent (with decreasing height) the gyroresonance layer locations for harmonics: 5 GHz $s = 3$, 5 GHz $s = 2$, 8 GHz $s = 3$, 8 GHz $s = 2$. 
3.4. Model Results

Below we present the atmosphere model results using the values fitted to the observations from Table 1. Figures 6 and 7 show the model brightness temperature images at the frequencies and polarizations of the VLA observations. In Figure 6 a Gaussian smoothing to account for VLA beam widths has been applied and represents the data used in the quantitative comparison with the observations as described above. Figure 7 is the same data before smoothing useful for the analysis below.

Figure 8 presents in more detail the observed and modeled brightness temperatures along the cross-section shown in Figure 2d and used in the fitting. As in Figure 5, the vertical dashed line marks the location where the direction of the section changes. The solid line corresponds to the observed temperatures, and the dashed line to the atmosphere model. For comparison, also shown with a dotted line are the brightness temperatures in an atmosphere model where the volume is parameterized as a completely plane-parallel single-component model with the bulk component parameters from Table 1. The model brightness temperature images for this single-component model are shown in Figure 9.

We note the following regarding the model results in comparison to observations:

i) As we can see in Figures 6a,b and 8a,b, the model reproduces a decrease in brightness temperature in RCP at 5 and 8 GHz in the northern part of the sunspot. The location, as judged from the images before smoothing (Figure 7a,b), is in agreement with the observations. However, in the smoothed images the area of reduced brightness temperature is less pronounced than the observed one (Figure 2a,b).

ii) The single-component model does not adequately reproduce the observations: there is no brightness temperature decrease in the northern part of the sunspot. Instead, as theoretically expected, the brightness temperature is lower in the southeast part of the sunspot toward the Sun disk center (Figure 9d) due to the smaller angle between the
magnetic field and the line of sight there. This further supports the claim made above based on the magnetic field magnitude contours at 1400 km above the Sun surface in Figure 3b that any magnetic field irregularities present are insufficient for the magnetic field structure alone to account for the decreased brightness temperature in the northern part of the sunspot within plane-parallel atmosphere models.

iii) The discrepancies between the model and the observed brightness temperatures in the southern part of the sunspot (see Figure 8a,c,d) suggest that even with the use of a cross-section, the impact of the bright areas on perturbing the brightness temperature is not completely avoided.

In the data in Section 2, we note feature III, an area near (360″, 396″) (location marked with a cross in Figure 2d) within the broader reduced brightness temperature area in the northern part of the sunspot, where the sunspot brightness temperature in the RCP in 8 GHz exceeds the brightness temperature in 5 GHz. In Figure 10, we show the difference $T_{B,8\text{ GHz}} - T_{B,5\text{ GHz}}$ between the RCP brightness temperature in 8 GHz and in 5 GHz for data from (a) the VLA observations, (b) our model before the application of the Gaussian smoothing in accordance with VLA beam widths, and (c) our model after smoothing. Qualitatively, before smoothing, our model reproduces the brightness temperature inversion at this location. However, as with the overall reduced brightness temperature area in the northern part of the sunspot, the application of the Gaussian smoothing to account for the beam width diminishes the effect.

For this same location (marked with a cross in Figure 2d) of brightness temperature inversion with frequency within the area of reduced brightness temperature, in Figure 11, we
Figure 7  Model brightness temperature images at the three VLA observing frequencies and in both right and left circular polarizations (RCP and LCP, respectively) before the application of the Gaussian smoothing to account for VLA beam widths. Overlaid are contours of the sunspot umbra and penumbra.

Figure 8  The observed (solid) and modeled (dashed) brightness temperatures at the three VLA observing frequencies and in both right and left circular polarizations (RCP and LCP, respectively) along the cross-section used in the fitting. Also shown (dotted) the brightness temperatures for a single-component plane-parallel model.
Figure 9  Model brightness temperature images at the three VLA observing frequencies and in both right and left circular polarizations (RCP and LCP, respectively) for a single-component plane-parallel model. Overlaid are contours of the sunspot umbra and penumbra.

Figure 10  Images of the difference between the RCP brightness temperature in 8 GHz and in 5 GHz for data from (a) the VLA observations, (b) the model atmosphere before the Gaussian smoothing in accordance with VLA beam widths, and (c) the model atmosphere after smoothing. Overlaid are contours of the sunspot umbra and penumbra.

investigated in more detail the formation with height of the model brightness temperatures, which then allows for establishing the physical reason for the model results and the obtained fitted atmosphere models. Shown in the panels with respect to height along the Z-axis above the surface of the Sun are (from top): electron density, temperature, brightness temperatures
Figure 11  Model (a) electron density, (b) electron temperature, (c) brightness temperatures integrated along the ray path in the VLA observing frequencies and polarizations. (d)–(f) The free–free (dashed) and thermal gyroresonance (solid) opacities in the RCP at the three VLA observing frequencies with height along the Z-axis above the surface of the Sun near (360′′, 396′′) at the location of inverted with frequency brightness temperature. The vertical dashed lines mark the locations of gyroresonance layers as listed along the upper axis.

integrated along the ray path according to Equation 5 at the VLA observing frequencies and polarizations, and the free–free (dashed) and thermal gyroresonance (solid) opacities in the RCP at the three VLA observing frequencies. The vertical dashed lines mark the locations of gyroresonance layers as listed along the upper axis.

Focusing on the RCP as in Figure 10, we can see from Figure 11a,b that in our model at this location the open field component lies at heights between 8 and 27 Mm above the surface of the Sun. The relevant s = 2, 3, and 4 gyroresonance layers at 5 GHz sample the low-temperature open field component leading to the corresponding brightness temperature of $T_{B, \text{model}}^{5 \text{ GHz}} = 140\,000 \, \text{K}$ at this sunspot location before image smoothing. At 8 GHz the s = 2 harmonic is at the height of 3 Mm and is optically thick within the hot bulk component.
As a result, the brightness temperature reaches 870,000 K. The optical thickness due to both the higher gyroresonance layers lying within the open field component and the free–free emission in the dense plasma is insufficient to significantly decrease the brightness temperature with height, and it remains at \( T_{R,8 \text{ GHz}}^{B,\text{model}} = 660,000 \text{ K} \) before smoothing. At 15 GHz the model brightness temperature is set by the free–free emission within the dense open field component leading to a steady increase with height to \( T_{R,15 \text{ GHz}}^{B,\text{model}} = 15,000 \text{ K} \).

The physical explanation of the existence of an optimal fit with respect to the electron density and temperature of the open field component is as follows:

i) The decrease in model brightness temperature in the northern part of the sunspot, predominantly due to optically thick gyroresonance emission from gyroresonance layers within the open field component will be more pronounced the lower is the electron temperature there.

ii) Within the model of Alissandrakis, Kundu, and Lantos (1980), Equations 1 and 2, an isothermal temperature profile leads to a density profile that is exponentially decreasing with height (see Figure 5a), where the exponent is inversely proportional to temperature. Thus a lower temperature leads to a more rapidly decreasing density.

iii) Further to north of the previously investigated location, now within the area of reduced brightness temperature in the penumbra, near (360′′, 400′′), the open field component starts sufficiently high in the atmosphere (see Figures 4a,b and 5b) that the 5 GHz s = 2 harmonic layer is located lower in height and within the hot bulk component. This leads to high brightness temperature, which is then reduced due to free–free emission within the dense open field component. Since opacity increases with density, the density must be sufficiently large to significantly reduce the brightness temperature and thus for the reduced brightness area to extend north beyond the sunspot umbra and include the penumbra.

iv) Since at 15 GHz the brightness temperature is determined by the free–free emission from the dense open field component, a larger density leads to an increase in model brightness temperature at 15 GHz in the northern part of the sunspot. At even larger densities, however, the bright area extends northward even beyond the sunspot penumbra in disagreement with observations.

The four counteracting effects listed above lead to an optimal fit electron temperature and density for the open field component within our atmosphere model.

As already was noted in the Introduction, Brosius and White (2004) and Brosius and Landi (2005) observed a plume at the location of the reduced microwave emission for this sunspot in coordinated EUV observations with SOHO/CDS. For the plume, they reported temperatures between \( 1.6 \times 10^5 \) and \( 5.0 \times 10^5 \text{ K} \). In our model the best fit is obtained with a slightly lower temperature of \( 1.4 \times 10^5 \text{ K} \). As for the density, the value previously reported for the logarithm of the electron density is \( 9.4 \pm 0.2 \). In our model the density of the open field component exponentially decreases from log \( n_0 = 9.8 \) with the characteristic values of log \( n_0 > 9 \) at the relevant heights.

The above analysis used a magnetic field model based on a PFSS extrapolation with \( R_{SS} = 1.8 \text{ R}_\odot \). The source-surface was purposefully chosen to be lower than the standard \( R_{SS} = 2.5 \text{ R}_\odot \) since it leads to an increase in the volume of open field, and the features of reduced brightness temperature in model images due to the open field component are almost too small to be apparent after smoothing even with \( R_{SS} = 1.8 \text{ R}_\odot \). In Figure 12, we illustrate the results of using a magnetic field model based on a PFSS extrapolation with \( R_{SS} = 2.5 \text{ R}_\odot \) and the same fitted atmosphere parameters from Table 1. Figure 12a is the same as Figure 4c except for the use of \( R_{SS} = 2.5 \text{ R}_\odot \) in the extrapolation. Open fields are still present and at
the same location within the sunspot, but in this case, at the lower heights (solid line) the volume of open field is narrower than with $R_{SS} = 1.8 \, R_\odot$. The open field lines again initially continue northward, spread out with increasing height, and eventually a significant portion continues southward across the model volume (not shown). However, this takes place at larger heights as expected with an increased source-surface height.

Figures 12b and 12c show the model brightness temperature images before and after smoothing, respectively, in the RCP at 5 GHz with $R_{SS} = 2.5 \, R_\odot$ magnetic field extrapolation and with the same fitted atmosphere parameter values as for $R_{SS} = 1.8 \, R_\odot$. Qualitatively, the atmosphere model still produces a reduced brightness temperature area in the northern part of the sunspot at the correct location of the observational feature II. However, the area is even narrower than in the $R_{SS} = 1.8 \, R_\odot$ model before smoothing (compare Figures 12b and 7a), and the effect is barely noticeable in the image after smoothing.

4. Discussion and Conclusions

We have constructed a model volume for the atmosphere above the sunspot of AR 8535. We performed a high-resolution PFSS reconstruction to determine the magnetic field for the volume while also identifying an open magnetic field line subvolume. We used the model of Alissandrakis, Kundu, and Lantos (1980) to parameterize the atmospheres of the two subvolumes or components, the bulk component and the open field component. For the latter to achieve better agreement with observations, we further explored the case of isothermal plasma and varied the constant-with-height temperature as a parameter. The bulk component determines the overall size and temperature of the sunspot in microwaves. Varying the density and temperature of the open field component produces opposing effects at different frequencies and regions of the sunspot, thus allowing for optimization. We emphasize the following results and conclusions:

i) In our high-resolution magnetic field modeling, we identify an open field line volume spatially coincident with the location of reduced brightness temperature in the VLA 5 and 8 GHz RCP images (compare Figures 4c and 12a with Figures 2a,b).
ii) Our model, which includes a dense low-temperature isothermal component in the open field line subvolume, qualitatively reproduces the brightness temperature decrease in the northern part of the sunspot in the VLA 5 and 8 GHz RCP images.

iii) The reduced brightness temperature feature in the model images becomes significantly less distinct and is less pronounced in comparison to the observations after the Gaussian smoothing to match the VLA resolution has been applied to the images. This suggests that the atmosphere subvolume with dense low-temperature plasma is broader than the modeled one and was the motivation for performing the PFSS magnetic field extrapolation with the source-surface at $R_{SS} = 1.8 R_\odot$. As stated in Section 3.2, whereas such a choice is not unprecedented, the required broader low-temperature plasma volume beyond that predicted by the standard $R_{SS} = 2.5 R_\odot$ modeling may be instead due to sufficiently cold and dense plasma also along the closed loops neighboring the open field volume. After all, in reality a gradient between the bulk and the open field components instead of the sharp boundary in the present model is to be expected. As shown in Figure 12, modeling with $R_{SS} = 2.5 R_\odot$ still reproduces the open field volume and reduced brightness temperature in the northern part of the sunspot, though not as extensive as observed.

iv) The sunspot microwave images contain three areas of increased brightness temperature that also correspond to areas of brightness temperature inversion with frequency. Due to this coincidence and likely magnetic linkage between gyroresonance layers for the different frequencies corresponding to these bright areas, we postulate that physically these represent flux tubes with higher electron temperature in the lower atmosphere layers. For these three areas, which are away from the region of reduced brightness temperature in the northern part of the sunspot, our explanation is different from the cases of Gary and Hurford (1994) and, most recently, of Tun, Gary, and Georgoulis (2011), where brightness temperature inversion with frequency was due to absorption in cool overlying loops. Although here we do not further elaborate on the nature or source of the temperature structure in these flux tubes, such an investigation is warranted in the future including a relation, possibly through magnetic reconnection, to the neighboring open fields that we establish.

v) The atmosphere model bulk component alone leads to brightness temperature images (Figure 9) that do not reproduce the brightness temperature decrease in the northern part of the sunspot. As is also suggested by the featureless magnetic field magnitude contours in Figure 3b, it is unlikely that the brightness temperature decrease is due to magnetic field irregularities alone and is not reproducible with a single-component plane-parallel atmosphere model.

vi) We conclude that, at least for this particular sunspot of AR 8535, the low-temperature plasma already observed and described generally as a sunspot plume (Brosius and White, 2004) is also consistent with the alternative interpretation of low-temperature plasma lying along open field lines.

We did not attempt to model the areas of increased brightness temperature, feature I from Section 3.1. Hence, for the model fit evaluation, we used cross-sections instead of the complete images. However, Figures 8a,c,d suggest that the impact of the bright areas on perturbing the brightness temperature was not completely avoided. More complete accounting for the bright areas may allow for more accurate model fitting.

The model presented here is admittedly empirical and limited. Whereas within the employed atmosphere model both bulk and open field components are in hydrostatic equilibrium, no equilibrium considerations between the two components are investigated. Likewise, no flows are modeled even though they may be of importance on open field lines. For the
closed field lines, analysis similar to that in Fleishman et al. (2021) may provide useful further insights.

The low-temperature plasma overlying the hotter plasma leads to brightness temperature inversion with frequency (Figures 10b and 11c), as was observed by Gary and Hurford (1994) and Tun, Gary, and Georgoulis (2011). In our model, however, the cold plasma affects emission already in the gyroresonance layers and lies along open field lines rather than along closed loops. This distinction between closed and open field lines and the resulting effect on plasma transport is important if a more complete physical model is to be established for our proposed empirical density and temperature profiles.

The magnetic field modeling was done using the PFSS reconstruction, which allowed for consistent field extrapolation for both the atmosphere model volume and the global model used for identifying open field lines. However, the method most notably assumes the absence of currents in the modeling volume. The modeling can be improved by relaxing this assumption and using the more general (and complex) nonlinear force–free field extrapolation for the atmosphere model volume. Proper care must be taken to then accurately relate the open field lines from the global model to voxels in the atmosphere model volume.

Our present investigation was limited to a single sunspot, but we propose repeating the analysis for other sunspots with radio observations in several frequencies that have either been determined to contain a low-temperature plasma volume (see Introduction) or that display dark lanes in EUV and X-ray images. Observations in many closely spaced frequencies, for example, using the Expanded Owens Valley Solar Array (EOVSA; Gary et al., 2018) or the proposed Frequency-Agile Solar Radiotelescope (FASR; Gary and Keller, 2004), are of particular interest. For gyroresonance emission, such measurements would provide effectively a scan in emission with height since gyroresonance layers are located at progressively lower heights with higher observing frequency. Then the already mentioned IDL-based software package GX_Simulator for calculating the expected multifrequency microwave, X-ray, and EUV emission of modeled ARs can be used for more comprehensive modeling that incorporates all these frequency ranges.

The connection between open fields and the resulting plasma temperature and density change is of relevance for research on the source of slow solar wind and suggests further investigation of plasma flows in the atmosphere of this sunspot and with respect to our presented atmosphere structure.

Overall, we demonstrate that radio images of the sunspot of AR 8535 provide a wealth of information regarding its atmosphere, which in our interpretation contains flux tubes with higher temperature lower in the atmosphere and open field lines with dense low-temperature plasma.

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**Declarations**

**Disclosure of Potential Conflicts of Interest** The authors declare that they have no conflicts of interest.
References

Abbo, L., Ofman, L., Antiochos, S.K., Hansteen, V.H., Harra, L., Ko, Y.-K., Lapenta, G., Li, B., Riley, P., Strachan, L., von Steiger, R., Wang, Y.-M.: 2016, *Space Sci. Rev.* 201, 55. DOI.

Alissandrakis, C.E., Kundi, M.R.: 1982, *Astrophys. J.* 253, L49. DOI.

Alissandrakis, C.E., Kundi, M.R., Santos, P.: 1980, *Astron. Astrophys.* 82, 30.

Alissandrakis, C.E., Bogod, V.M., Kaltman, T.L., Patsourakos, S., Peterova, N.G.: 2019, *Solar Phys.* 294, 23. DOI.

Altschuler, M.D., Newkirk, G.: 1969, *Solar Phys.* 9, 131. DOI.

Bale, S.D., Badman, S.T., Bonnell, J.W., Bowen, T.A., Burgess, D., Case, A.W., Cattell, C.A., Chandran, B.D.G., Chaston, C.C., Chen, C.H.K., Drake, J.F., Dudok de Wit, T., Eastwood, J.P., Ergun, R.E., Farrell, W.M., Fong, C., Goetz, K., Goldstein, M., Goodrich, K.A., Harvey, P.R., Horbury, T.S., Howes, G.G., Kasper, J.C., Kellogg, P.J., Klimchuk, J.A., Korreck, K.E., Krasnoselskiikh, V.V., Krucker, S., Laker, R., Larson, D.E., MacDowall, R.J., Maksimovic, M., Malaspina, D.M., Martinez-Oliveros, J., McComas, D.J., Meyer-Vernet, N., Moncuquet, M., Mozer, F.S., Phan, T.D., Pulupa, M., Raouafi, N.E., Salem, C., Stansby, D., Stevens, M., Szabo, A., Velli, M., Woolley, T., Wygant, J.R.: 2019, *Nature* 576, 237. DOI.

Bezrukov, D.A., Ryabov, B.I., Shibasaki, K.: 2012, *Balt. Astron.* 21, 509. DOI.

Bezrukov, D.A., Ryabov, B.I., Shibasaki, K.: 2012, *Balt. Astron.* 21, 509. DOI.

Bezrukov, D., Ryabov, B., Peterova, N., Topchilo, N.: 2011, *Latv. J. Phys. Tech. Sci.* 48, 56. DOI.

Brosius, J.W., Landi, E., Peterova, N., Topchilo, N.: 2011, *Latv. J. Phys. Tech. Sci.* 48, 56. DOI.

Brosius, J.W., White, S.M.: 2004, *Astrophys. J.* 601, 546. DOI.

Brosius, J.W., Landi, E., Cook, J.W., Newmark, J.S., Gopalswamy, N., Lara, A.: 2002, *Astrophys. J.* 574, 453. DOI.

Delaboudinière, J.-P., Artzner, G.E., Brunaud, J., Gabriel, A.H., Hochedez, J.F., Millier, F., Song, X.Y., Au, B., Dere, K.P., Howard, R.A., Kreplin, R., Moses, J.D., Defise, J.M., Jamor, C., Rochus, P., Chauvineau, J.P., Marioge, J.P., Catura, R.C., Lemen, J.R., Shing, L., Stern, R.A., Garman, J.B., Neupert, W.M., Maucherat, A., Clette, F., Cugnon, P., Van Dessel, E.L.: 1995, *Solar Phys.* 162, 291. DOI.

Dulk, G.A.: 1985, *Annu. Rev. Astron. Astrophys.* 23, 169. DOI.

Fleishman, G.D., Anfinogentov, S.A., Stupishin, A.G., Kuznetsov, A.A., Nita, G.M., Shih, A.Y., White, S.M., Yu, S.: 2018, *Astrophys. J.* 863, 83. DOI.

Gelfreikh, G.B.: 2004, In: Gary, D.E., Keller, C.U. (eds.) *The Physics of Sunspots: Proc. Sac. Peak Obs.*, 191.

Gelfreikh, G.B.: 2004, In: Gary, D.E., Keller, C.U. (eds.) *The Physics of Sunspots: Proc. Sac. Peak Obs.*, 191.

Gary, D.E., Hurford, G.J.: 1994, *Astrophys. J.* 420, 903. DOI.

Gary, D.E., Keller, C.U. (eds.): 2004, *Solar and Space Weather Radiophysics – Current Status and Future Developments*, Kluwer, Dordrecht. DOI.

Gary, D.E., Chen, B., Dennis, B.R., Fleishman, G.D., Hurford, G.J., Krucker, S., McInternan, J.M., Nita, G.M., Shih, A.Y., White, S.M., Yu, S.: 2018, *Astrophys. J.* 863, 83. DOI.

Gelfreikh, G.B.: 2004, In: Gary, D.E., Keller, C.U. (eds.) *Solar and Space Weather Radiophysics – Current Status and Future Developments*, Kluwer, Dordrecht, 115. DOI.

Gibson, S.E., Kucera, T.A., White, S.M., Dove, J.B., Fan, Y., Forland, B.C., Rachmeler, L.A., Downs, C., Reeves, K.K.: 2016, *Front. Astron. Space Sci.* 3, 8. DOI.

Kakinuma, T., Swarup, G.: 1962, *Astrophys. J.* 136, 975. DOI.

Lee, J.: 2007, *Space Sci. Rev.* 133, 73. DOI.

Lee, J., McClymont, A.N., Mikić, Z., White, S.M., Kundi, M.R.: 1998, *Astrophys. J.* 501, 853. DOI.

Lee, C.O., Luhmann, J.G., Hoeksema, J.T., Sun, X., Arge, C.N., de Pater, I.: 2011, *Solar Phys.* 269, 367. DOI.

Lokitcheva, M.A., Iwai, K., Solanki, S.K., White, S.M., Shimojo, M.: 2017, *Astrophys. J.* 850, 35. DOI.

Mok, Y., Mikić, Z., Lionello, R., Downs, C., Linker, J.A.: 2016, *Astrophys. J.* 817, 15. DOI.

Nindos, A., Alissandrakis, C.E., Gelfreikh, G.B., Kundi, M.R., Dere, K.P., Korzhavin, A.N., Bogod, V.M.: 1996, *Solar Phys.* 166, 55. DOI.

Nita, G.M., Viall, N.M., Klimchuk, J.A., Lokitcheva, M.A., Gary, D.E., Kuznetsov, A.A., Fleishman, G.D.: 2018, *Astrophys. J.* 853, 66. DOI.

Robinson, P.A., Melrose, D.B.: 1984, *Aust. J. Phys.* 37, 675. DOI.

Ryabov, B.I., Shibasaki, K.: 2016, *Balt. Astron.* 25, 225. DOI.

Ryabov, B.I., Vrublevskis, A.: 2020, *Solar Phys.* 295, 4. DOI.

Ryabov, B.I., Gary, D.E., Peterova, N.G., Shibasaki, K., Topchilo, N.A.: 2015, *Solar Phys.* 290, 21. DOI.

Schatten, K.H., Wilcox, J.M., Ness, N.F.: 1969, *Solar Phys.* 6, 442. DOI.

Scherrer, P.H., Bogart, R.S., Bush, R.I., Hoeksema, J.T., Kosovichev, A.G., Schou, J., Rosenberg, W., Springer, L., Tarbell, T.D., Title, A., Wolfson, C.J., Zayer, I. (MDI Engineering Team): 1995, *Solar Phys.* 162, 129. DOI.
Schrijver, C.J., DeRosa, M.L.: 2003, Solar Phys. 212, 165. DOI.
Strong, K.T., Alissandrakis, C.E., Kundu, M.R.: 1984, Astrophys. J. 277, 865. DOI.
Stupishin, A.G., Kaltman, T.I., Bogod, V.M., Yasnov, L.V.: 2018, Solar Phys. 293, 13. DOI.
Tun, S.D., Gary, D.E., Georgoulis, M.K.: 2011, Astrophys. J. 728, 1. DOI.
Vourlidas, A., Bastian, T.S., Aschwanden, M.J.: 1997, Astrophys. J. 489, 403. DOI.
White, S.M., Kundu, M.R., Gopalswamy, N.: 1991, Astrophys. J. 366, L43. DOI.
Zheleznyakov, V.V.: 1962, Soviet Astron. 6, 3.
Zlotnik, E.Y., Kundu, M.R., White, S.M.: 1996, Radiophys. Quantum Electron. 39, 255. DOI.
Zlotnik, E.Y., White, S.M., Kundu, M.R.: 1998, In: Alissandrakis, C.E., Schmieder, B. (eds.) Second Advances in Solar Physics Euroconference: Three-Dimensional Structure of Solar Active Regions, ASP Conf. Series 155, 135.

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