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POLARIZATION OF THE THERMAL RADIO EMISSION FROM OUTER SOLAR CORONA

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ABSTRACT

The Haselgrove equations for radio-ray propagation in an anisotropic medium are used to determine the degree of circular polarization (dcp) of the low-frequency thermal radio emission from the outer solar corona with a magnetic field. The variation of dcp with frequency and magnetic field strength is investigated. It is found that weak magnetic fields can be detected by measuring the dcp at low frequencies.

Key words: Sun: activity – Sun: corona – Sun: magnetic fields – Sun: radio radiation

1. INTRODUCTION

Direct measurements of magnetic field strength in the outer corona at heights $\geqslant 0.2\ R_\odot$ ($R_\odot$ = radius of the Sun = 6.96×10^5 km) have not yet been obtained although magnetic fields are believed to play an important role in the dynamics of the corona as well as the formation of various structures there. The magnetic field strength in the corona is generally found from the extrapolation of optical measurements of photospheric field, using the potential field source surface model. Lin et al. (2000) reported measurements of field strengths from observations of the Stokes V profiles of the coronal emission line Fe xiii λ10747 resulting from the longitudinal Zeeman effect of the coronal magnetic field. They measured field strengths of 10 and 33 G above active regions at heights of 0.12 and 0.15 $R_\odot$, respectively. In the radio domain, high-resolution circular polarization observations in the frequency range 1–20 GHz are routinely used (Gelfreikh 2004; Ryabov 2004; White 2004, and the references therein) to measure the field strengths above active regions at heights $\simeq 0.05\ R_\odot$ since the pioneering work of Kakinuma & Swarup (1962). The radio emission from the "undisturbed" Sun, streamers, and holes at heights $\geqslant 0.2\ R_\odot$ lies at frequencies $\leqslant$100 MHz. The thermal nature of this radiation is recognized since the work of Smerd (1950). Surprisingly, it was never pointed out that this fact can be used to directly measure the strength of the magnetic fields, which are known to exist in the outer corona. Also no attempt to detect the polarization characteristics of the continuum radiation from the "undisturbed" Sun has ever been made although polarization measurements of the radio bursts are quite common, see for e.g., Sastry (1973). The primary objective of the present work is to point out the possibility of using thermal radiation for measuring magnetic field strength in the outer corona. The method is not applicable at frequencies and regions where the outer corona is optically thick for thermal radiation.

2. RAY PATHS

2.1. Application of Magnetoionic Theory

The presence of a magnetic field makes the corona anisotropic and the initially unpolarized thermal radiation propagates in two oppositely polarized circular modes: ordinary and extraordinary. The difference in the total optical depth of the above two modes depends on the prevailing magnetic field strength. The magnetoionic theory is used to determine the ray paths of the two modes. Here it is assumed that the solar corona is cold for the purpose of calculating the dispersion relations and to trace the rays, and hot to calculate the damping. These assumptions are justified provided the phase speeds of the waves are much greater than the thermal speeds of electrons. The phase speeds in the present case are all greater than the speed of light and so the cold plasma approximation is valid (Stix 1962; Melrose 1980, 1985; Benz 2002; D. B. Melrose 2007, private communication).

2.2. Haselgrove Equations

In an inhomogeneous anisotropic medium the energy associated with electromagnetic waves does not in general travel in the direction of the wave normal even in the case of plane waves but in a different direction called the ray path. The ray refractive index of the corona at a low radio frequency varies from zero (at the level where the plasma and observing frequencies are equal) to unity (at a large distance away from the Sun) and so the ray paths are not straight but curved. To estimate the total optical depth of either of the modes, the ray path along which the energy propagates has to be found and the absorption coefficient is integrated along the path. The ray refractive index is not known a priori but information on the phase refractive index which is a function of the position and direction of the wave normal can be derived from the Appleton–Hartree equation. Haselgrove (1955), Haselgrove & Haselgrove (1960), and Haselgrove (1963) in three seminal papers derived a set of differential equations to determine the rate of change of the wave normal direction along the ray path in terms of phase refractive index and its derivatives, in a magnetized plasma. These equations are based on Hamilton's canonical equations of geometrical optics. The Haselgrove equations in two dimensions were used by Golap & Sastry (1994) to derive the one-dimensional brightness distribution of the outer corona at a frequency of 30 MHz for the two circular modes.

The Haselgrove equations in the cartesian coordinates with origin at the center of the Sun are used in the present work. The notation adopted is same as that of Haselgrove (1963) and is as follows:

1. x_1, x_2, x_3: Cartesian coordinates of a point on the ray path.
2. u_1, u_2, u_3: components of a vector $\vec{u}$ parallel to the wave normal at the point x_1, x_2, x_3 and of length u equal to the refractive index at that point and for that direction of the wave normal.
3. X: magnetoionic parameter = f_p^2/f^2, where f_p is the plasma frequency and f is the wave frequency.

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4. Y_1, Y_2, Y_3: components of a vector $\vec{Y}$ parallel to the magnetic field and of length equal to the magnetoionic parameter $Y = f_H/f$, where f_H is the gyro frequency.
5. $q = (u^2 - 1)/X$: the values of q for the ordinary and extraordinary modes are obtained from the Appleton–Hartree equation.
6. t: independent variable.

The differential equations are

$$dx_i/dt = Ju_i - KY_i \quad (1)$$

$$du_i/dt = L\partial X/\partial x_i + \sum_j (Ku_j + MY_j)\partial Y_j/\partial x_i \ (i = 1, 2, 3), \quad (2)$$

where
$J = 2(1 - X + Y^2)(q + 1) + Y^2 + (\vec{Y} . \vec{u})^2$
$K = -2qX(\vec{Y} . \vec{u})$
$L = (1 - Y^2)(q + 1)^2 - 2(1 - X - Y^2)(q + 1) - Y^2$
$M = 2qX(q + 1)$.

Further details can be found in Haselgrove (1963). The differential equations are integrated separately for the ordinary and extraordinary modes using the Matlab ODE Suite which is based on Runge–Kutta–Fehlberg methods.

3. ABSORPTION COEFFICIENT

In the magnetoionic theory, the absorptive index is the imaginary part of the complex refractive index given by the Appleton–Hartree equation. The absorption coefficient is propagation constant in free space times the absorptive index. Depending on the angle between the wave vector and the direction of the magnetic field, the absorption coefficient is usually separated into longitudinal and transverse parts. At GHz frequencies, where the ray path is straight, the longitudinal part is only used since it is valid except for angles close to 90°. At these frequencies, the magnetoionic parameters X and Y are both $\ll$1 and so the expressions of the absorption are simplified. At the frequencies of interest in the present work in the outer corona X varies from zero to unity and Y can take values close to unity, depending on the frequency, along the ray path. However, the magnetoionic parameter $Z = \nu/\omega$ (where ν is the collision frequency given by Scheuer 1960) is $\ll$1.

The angle between the wave vector and the direction of the magnetic field varies along the ray path and goes through 90° at the reflection level. In the present investigation both the longitudinal and transverse parts of the absorption coefficient are used. But it should be noted that the path length over which the ray turns is found to be small compared to the total path traversed by the ray and the contribution of the transverse absorption coefficient to the total optical depth is very small, although its magnitude is much larger than the longitudinal absorption coefficient. The full expressions for the absorption coefficients for the ordinary and extraordinary modes and for the longitudinal and transverse propagation are the following:

1. Longitudinal propagation:

$$k_o = \frac{k_n(1 - X)^{1/2}}{(1 + |Y_l|)^{3/2}(1 - X + |Y_l|)^{1/2}}$$

$$k_e = \frac{k_n(1 - X)^{1/2}}{(1 - |Y_l|)^{3/2}(1 - X - |Y_l|)^{1/2}}.$$

2. Transverse propagation:

$$k_o = k_n$$

$$k_e = \frac{k_n\left[1 + Y_t^2/(1 - X)^2\right]}{\left[1 - Y_t^2/(1 - X\right]^{3/2}\left[1 - Y_t^2/(1 - X)^2\right]^{1/2}}.$$

The subscripts "o" and "e" refer to the ordinary and extraordinary modes and "t" and "l" refer to the transverse and longitudinal components of the magnetic field. k_n is the absorption coefficient in the absence of the magnetic field. The dcp is defined as, $\frac{T_b^E - T_b^O}{T_b^E + T_b^O} \times 100$, where T_b^O and T_b^E are the brightness temperatures of the ordinary and extraordinary modes, respectively.

4. THE ELECTRON DENSITY AND MAGNETIC FIELD MODELS

The coronal electron density model used is that of Newkirk (1961) which is found to give a good fit to the observed brightness distributions at low frequencies. The presence of a coronal hole/density enhancement is included by writing the model as

$$N(R) = 4.2 \times 10^4 \times D \times 10^{(4.32/R)}[1 + Ce^{-\beta^2/2\sigma^2}]\,\mathrm{cm}^{-3}, \quad (3)$$

where

1. R is the radial distance in units of $R_\odot$,
2. $\beta^2 = (x_1 - R\sin\theta\cos\phi)^2 + (x_2 - R\sin\theta\sin\phi)^2 + (x_3 - R\cos\theta)^2$,
3. σ is the width of streamer/hole in units of $R_\odot$,
4. θ, ϕ are polar and azimuthal angles of the center of the streamer/hole, respectively,
5. D is the multiplication factor for the Newkirk density model of the "background" corona,
6. C is the factor of density increase/decrease in coronal streamer/hole.

The above model is adopted since it has been used with considerable success by several authors in the past to reproduce/interpret density enhancement/depletion in the corona (Riddle 1970; Sastry, et al. 1983; Sheridan & McLean 1985; Thejappa & Kundu 1994; Ramesh & Sastry 2000; Kathiravan, et al. 2002). The model is used to illustrate the polarization effects of the magnetic field on the thermal radiation of the "undisturbed" Sun, streamers, and holes. It is found that the above model with $D = 0.5$ gives a better fit to the low frequency observations of the "undisturbed" Sun during sunspot minimum (Thejappa & Kundu 1992). The dcp is therefore calculated for $C = 0$ and values of $D = 1$ and 0.5 for the "undisturbed" Sun. Values of C ranging from 2 to 10 have been used by various workers depending on the measured brightness temperature (T_b) of a streamer (Sastry et al. 1981; Sastry, et al. 1983). In the present analysis a value of $C = 5$ is adopted as a reasonable choice for the coronal streamer. Coronal holes have been identified as brightness temperature depressions at meter and decameter wavelength radio observations. Munro & Withbroe (1972) and Perry & Altschuler (1973) deduced that the electron density in coronal holes is 0.1–0.5 times that of the ambient corona from whitelight observations. The metric and decametric radio observations (Dulk & Sheridan 1974; Wang, et al. 1987; Subramanian & Sundaram 2005) showed that the electron density in coronal holes decreases by factors of 2–4 compared to the ambient corona and so $C = -0.75$ is used in the present study. It should be noted that coronal holes at low frequencies are seen in emission by some authors (Dulk & Sheridan 1974; Lantos et al. 1987). But the present calculations apply to coronal holes seen as depressions only.

The widely used model for the variation of the strength of the magnetic field with solar distance is due to Dulk & McLean (1978) and is based on observations of various types of radio bursts. It is therefore applicable for magnetic fields above active regions. In the present investigation, the model is adopted with a slight variation given by

$$\vec{B}(R) = \frac{B_o}{[R-1]^{1.5}}\hat{r} \quad (1.02\,R_\odot < R < 10\,R_\odot), \qquad (4)$$

where $\hat{r}$ is the unit vector in the radial direction. The constant B_o is adjusted to give the assumed value of the magnetic field strength at the plasma level of the observing frequency. The field lines pointed towards the observer are taken to be positive. The same model is adopted for the variation of the field strength with solar distance for both the "undisturbed" Sun and coronal holes since the models of field strength variation in the heliocentric distance range 5–12 $R_\odot$ measured at various times by Patzold et al. (1987) and Spangler (2005) are similar to the Dulk & McLean (1978) model. The structure of the magnetic field is believed to consist of open field connections between the solar surface and the heliosphere. These are inferred from observations and modeling. Observational techniques include identification of coronal intensity features with magnetic field lines, paths of Type III radio bursts, extrapolation of spacecraft observations into solar surface etc. Modeling consists of outward numerical extrapolation of photospheric fields to a source surface with an imposed boundary condition of radial field lines. The source surface is believed to be typically located at a heliocentric distance of 2.5 $R_\odot$ (Nitta & DeRosa 2008). In coronal holes, Levine (1977) located it at 1.3 $R_\odot$ to explain some features of coronal holes and Vrsnak et al. (2002) find that the field becomes radial at a heliocentric distance of 2 $R_\odot$ in active regions. In a series of publications, Woo (2005) and his associates produced direct evidence from HAO/Mauna Loa MK III K-Coronameter observations, radio scintillation data and spacecraft observations suggesting that the magnetic field is radial from heliocentric distances as low as 1.15 $R_\odot$ in the "undisturbed" corona. Hu et al. (2003) presented a two-dimensional magnetohydrodynamics (MHD) model in support of this interpretation.

5. RESULTS

The expected magnetic field strengths in the "undisturbed" outer corona at heliocentric distances, 1.5 $R_\odot \leqslant R \leqslant 3\ R_\odot$, are estimated from the average of the field strengths measured by Spangler (2005). He used the Faraday rotation technique on extragalactic radio sources at various times in the heliocentric distance range 6 $R_\odot \leqslant R \leqslant 10\ R_\odot$. The average field strength standardized to a distance of 6.2 $R_\odot$ measured by him is 40 mG. The earlier Faraday rotation measurements using the *HELIOS* spacecraft by Patzold et al. (1987) in the heliocentric distance range 3 $R_\odot \leqslant R \leqslant 10\ R_\odot$ correspond to a field strength of 57 mG at 6.2 $R_\odot$. These authors also found that the field strength varies as $R^{-\alpha}$, where $\alpha = -2.7 \pm 0.2$. Spangler (2005) arrives at a value of $\alpha = -2$ from his more recent observations. The latter value is used in the present investigation to find the reference field strengths at heliocentric distances of 1.5 $R_\odot \leqslant R \leqslant 3\ R_\odot$ and they vary from 800 to 200 mG. It is worthwhile to mention here that the potential field model may be used to locate the magnetic neutral line in the corona although the field strengths are underestimated by that model (S. R. Spangler, 2008 private communication). Bird & Edenhofer (1990); Ingleby, et al. (2007) also arrived at similar conclusions by comparing magnetic fields from Faraday rotation measurements and potential field extrapolations. In the heliocentric distance range of 1.5 $R_\odot \leqslant R \leqslant 3\ R_\odot$, the plasma frequencies in the corona vary from 30 to 10 MHz according to the Newkirk (1961) model with $D = 1$ and so the emitted radiation lies in the same frequency range. The distribution of the degree of polarization is calculated at each of the three frequencies 10, 20 and 30 MHz from the center to the limb in steps of 0.2 $R_\odot$ in the equatorial plane of the "radio" Sun. The field strength at each frequency is varied from 100 mG up to 1600 mG. Note that the model of Spangler (2005) is used to determine the reference field only and in the dcp calculations the model of Dulk & McLean (1978) is adopted. The latter is the only model available and supposedly more appropriate for field strength variations in the low corona although the difference in α between the two models (-2 & -1.5, respectively) is small. The maximum value of dcp at all the three frequencies occurs in the central regions of the "radio" Sun. The dcp versus field strength at each one of the three frequencies is plotted in Figure 1. The dcp increases with field strength at all the frequencies and for the same field strength the dcp increases with decreasing frequency. It is possible that field strengths of 200 mG can be detected from low-frequency circular polarization observations of the "undisturbed" Sun.

The magnetic field strength in the corona above active regions, estimated from radio burst observations, decreases from 1–8 G at 1.6 $R_\odot$ to 0.3–0.9 G at 2.5 $R_\odot$ according to Vrsnak et al. (2002). This result is in good agreement with other estimates at these heliocentric distances (Krüger & Hildebrandt 1993; Dulk & McLean 1978). The enhanced radio radiation emitted by coronal streamers with density larger by a factor ∼5 compared to the "undisturbed" Sun at heliocentric distances of 1.5 $R_\odot$ to 2.5 $R_\odot$ lies in the frequency range 80–20 MHz. A computation of the distribution of the dcp across the "radio" Sun by uniformly increasing the density ($D > 1$ in the Newkirk model) over the entire corona revealed that the dcp variations will be significant only at distances away from the center at frequencies around 80 MHz, for any magnetic field strength. This frequency is chosen as one of the operational frequencies of the Gauribidanur radioheliograph (Ramesh et al. 1998), Gauribidanur radio polarimeter (Ramesh & Sastry 2005; Ramesh et al. 2008) and the VLA[2] which is capable of measuring circular polarization with high resolution are close to it. The distribution of the dcp at 80 MHz across the "radio" Sun with a streamer incorporated at the limb is, therefore computed. For the Newkirk electron density model the distribution of dcp across the radio Sun is found to depend on the factor by which the density increases in the region of the streamer, orientation of the axis of the streamer (polar and azimuthal angles defined in Equation (3)), the strengths of the fields in the ambient and streamer regions, and the size of the streamer. In the present study the axis of the streamer is placed in the equatorial plane and the dcp is calculated at various distances from the center to the limb in steps of 0.2 $R_\odot$. The field strength is varied from 1 to 4 G at the 80 MHz plasma level in the streamer and a small ambient field strength (≈300 mG). The azimuth of the streamer

[2] The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by associated universities, Inc.

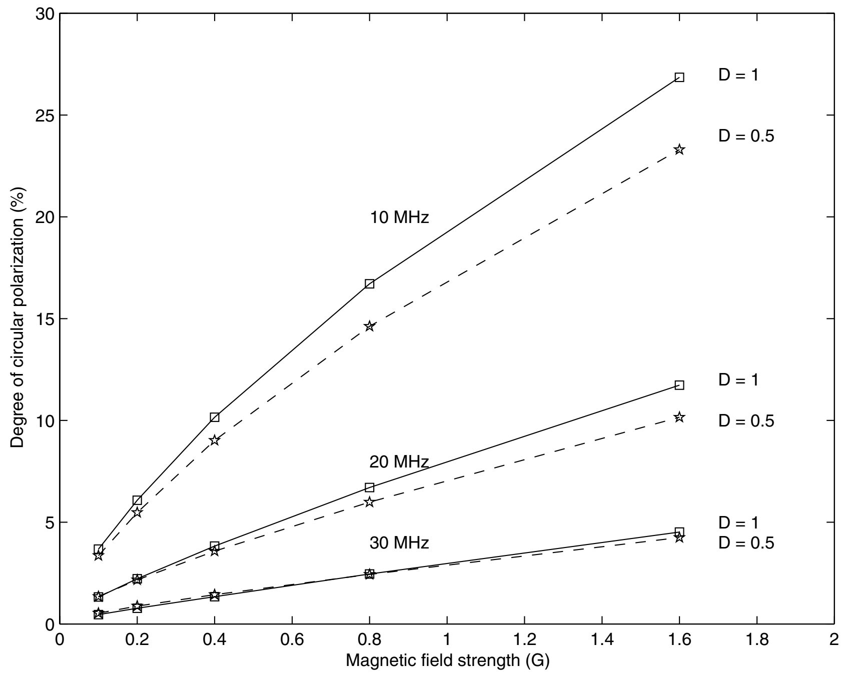

Figure 1. Variation of dcp with the magnetic field strength of the "undisturbed" Sun for 10, 20, and 30 MHz. The solid and dashed profiles at each frequency correspond to 1× and 0.5× Newkirk density model, respectively.

is set at 65° (almost the solar limb) and the width of the streamer is 10′. The distributions of the dcp across the "radio" Sun, for field strengths of 1, 2, and 4 G, are plotted in Figure 2. The brightness distribution of the ordinary and the extraordinary radiations for the case of the largest magnetic field strength (4 G) as well as the brightness distribution of the "undisturbed" Sun without the streamer, is also plotted. The parameters used in the computation of the dcp are given in Table 1. A comparison of the brightness distributions with and without streamer shows that the width of the "radio" Sun increases considerably in the presence of the streamer. The dcp attains the maximum value close to the half-power point, i.e., where the brightness temperature T_b of the *o* and *e* radiations become equal to half of their peak values, and increases with the field strength. Finally it is found that the dcp of the streamer increases with decreasing frequency for any magnetic field strength. From these results, it follows that when the location of the coronal streamer is near the limb of the "radio" Sun the effect of the magnetic field is maximum at frequencies around 80 MHz and its strength can be estimated by measuring the dcp of the emitted radio frequency thermal radiation.

Magnetic field lines in coronal holes are believed to be open from the base of the corona but there are no estimates of its strength in the outer coronal holes. As mentioned above the field strength is assumed to vary according to the Dulk & McLean (1978) formula both in the ambient Sun and the hole in the absence of any alternative model. There is no limit to the size of the coronal holes and a hole can occupy a large fraction of the disk. In the present study the size of the hole is taken to be 10′ and the axis is placed in the equatorial plane of the Sun with an azimuth of 65° (again at the solar limb like the streamer case). The field strength in the ambient corona is set to a small value of ≈300 mG and that in the hole is varied from 1 to 2 G. The distribution of the dcp at 80 MHz is computed by taking the value of $C = -0.75$ in the Newkirk density model. The distributions of the dcp in the equatorial plane of the "radio" Sun for field strengths in the hole of 1 and 2 G are plotted in Figure 3. The distributions of the ordinary and extraordinary brightness temperatures for the 2 G case and the brightness temperature without the hole are also plotted. The values of the dcp in the case of the hole are relatively larger than those of the streamer for the same field strengths. As in the case of the streamer it is found that the dcp increases with decreasing frequency of observation. It is also clear that the strength of the magnetic field can be estimated by measuring the dcp of the thermal radiation from the coronal holes.

6. DISCUSSION

The dcp of the thermal radiation due to the presence of the magnetic field in the direction of any point on the Sun and at any frequency depends on the magnitude of absorption coefficient k_n at various points in the path of the radiation or the total optical depth, in the absence of the magnetic field, in that direction. The presence of the magnetic field modifies k_n in such a way that the absorption coefficients of the ordinary and extraordinary radiations (i.e., the total optical depth) may differ resulting in a difference of the *o* and *e* brightness temperatures and so the emergent radiation will be circularly polarized. At high frequencies (greater than 80 MHz), the central thermal optical depth of the corona, in the absence of the magnetic field, is already large (Smerd 1950; Sheridan & McLean 1985) so that any change in the optical depth(s) due to the presence of the magnetic field has very little or no effect on the T_b of the *o* and *e* radiations, resulting in negligible dcp values. However, in the direction away from the center of the Sun, the thermal optical depth in the absence of the magnetic field reduces considerably. Therefore, in the presence of the magnetic field, the difference in the optical depths of *o* and *e* radiations can become large causing the emerging radiation to be circularly polarized. At low frequencies (⩽30 MHz) the central thermal optical depth of the corona, in the absence of the magnetic field, is small (Bracewell & Preston 1956; Sheridan & McLean 1985). So, circular polarization effect due to the presence of the magnetic

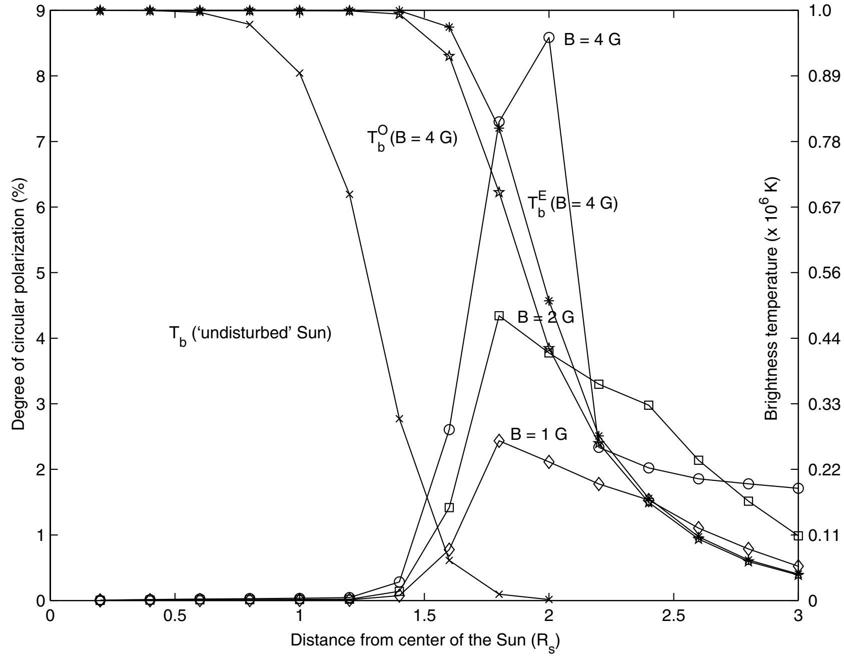

Figure 2. Extraordinary (asterisk) and ordinary (pentagram) brightness distributions of the "undisturbed" Sun (+ streamer with $B = 4$ G) at 80 MHz. The brightness distribution of the "undisturbed" Sun at 80 MHz without the streamer is indicated by the profile with "X" mark. The electron temperature of the corona was assumed to be 10^6 K. The variation in dcp with distance from the center of the Sun at 80 MHz when a "streamer" with different magnetic field strengths is included in the ray-tracing calculations. The field strengths used are 4 G (circle), 2 G (square), and 1 G (diamond).

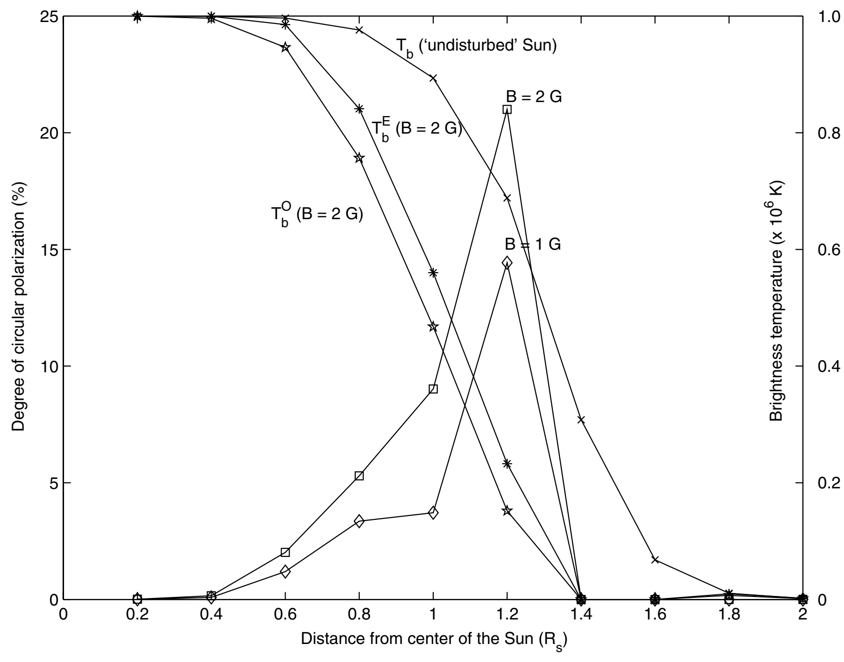

Figure 3. Extraordinary (asterisk) and ordinary (pentagram) brightness distributions of the "undisturbed" Sun (+ hole with $B = 2$ G) at 80 MHz. The brightness distribution of the "undisturbed" Sun at 80 MHz without the hole is indicated by the profile with "X" mark. The electron temperature of the corona was assumed to be 10^6 K. The variation in dcp with distance from the center of the Sun at 80 MHz when a "hole" with different magnetic field strengths is included in the ray tracing calculations. The field strengths used are 2 G (square), and 1 G (diamond).

Table 1
Parameters Used in the Computation of Figures 2 & 3 at 80 MHz

Source[a]	Density (Newkirk 1961)	Radial Distance	Magnetic Field
"Undisturbed" corona	$D = 1/C = 0$	1.3 $R_\odot$	300 mG
Streamer ($\theta = 90^\circ/\phi = 65^\circ$)	$D = 1/C = 5$	1.7 $R_\odot$	4, 2, 1 G
Hole ($\theta = 90^\circ/\phi = 65^\circ$)	$D = 1/C = -0.75$	1.1 $R_\odot$	2, 1 G

Note. [a] θ & ϕ = Polar and azimuthal angle, respectively.

fields can be seen even in that direction. These are the reasons for the occurrence of maximum dcp in the central directions at low frequencies and also for the increase of dcp with decreasing frequency.

The magnetic field of the "undisturbed" outer corona can be detected at low frequencies if the extrapolation of the fields measured in the interplanetary medium is valid. The magnetic field strength in a coronal streamer located anywhere on the Sun can be estimated at low frequencies. But at frequencies around 80 MHz where high-resolution observations are possible at present, the favorable location is the "radio limb" of the Sun at that frequency. These remarks also apply to the case of a coronal hole. The dcp of the latter is greater than that of a streamer for the same magnetic field strength because of the relatively small thermal optical depth in a coronal hole, in the absence of magnetic field.

It should be mentioned that due to assumed radial nature of the magnetic field the ray paths remain within the quasi-longitudinal limits (QL) of the magnetoionic theory over almost the entire path length and so there is no mode coupling. The present analysis is critically dependent on the existence of radial field lines and the absence of polarization effects in the thermal radiation may point to possibility of the magnetic field being complex. The low brightness temperatures sometimes observed at low radio frequencies are interpreted as due to the scattering of the radiation by coronal irregularities (Thejappa & Kundu 1992; Ramesh et al. 2006). There is no known process by which circular polarization effects will be reduced by such scattering.

I dedicate this work to the memory of my wife, Ch. V. Lakshmi, who for forty-six years gave me love, affection, and support. I thank R. Ramesh for discussions and help in various aspects of the work presented in this paper. D. B. Melrose and A. O. Benz are thanked for their kind help in clarifying Westfold's derivation of optical depths for ordinary and extraordinary modes, and application of magntoionic theory to determining ray paths in the corona. S. R. Spangler is thanked for providing details on Faraday rotation measurements of the coronal magnetic field and comparison with potential field calculations. I acknowledge the referee for his comments and suggestions on the earlier version of the manuscript.

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