ESTIMATE OF CORONAL MAGNETIC FIELDS FROM CONTOUR MAPS OF THE INTENSITY AND POLARIZATION DEGREE OF THE BURST ON 1992 OCTOBER 27

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ABSTRACT

In this paper contour maps at 17 GHz of the 1992 October 27 solar burst are analysed. Using a nonthermal inhomogeneous model of the radio source, variations of calculated brightness temperature with distance from the projected center of the source is in better agreement with the observed map at 01:45:29,889 UT. The calculation shows that the characteristic magnetic field gradient \( \alpha_n \) (magnetic field distribution is \( B_n(r/r_m) = 2000(r/r_m)^{-2} \)) at the peak of the 17 GHz emission is about 2, magnetic strength \( B \) is about 737 G with the magnetic field \( B_m \) of the core being 2000 G. On the other hand, from the polarization contour map and the “limiting polarization” concept, we obtain a magnetic moment \( d = 1.4 - 2.5 \times 10^{32} \) cgs units, and a coronal magnetic field \( B = 20 - 30 \) G at the height of \( 1.7 - 1.9 \times 10^{10} \) cm.

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INTRODUCTION

Radio measurements of the coronal magnetic field are very important since Zeeman splitting cannot be easily measured in the solar corona. There are two difficulties in the homogeneous models. They can not explain the flat spectrum of solar radio bursts on the high frequency side and the projected area of the source varying with frequency (Crummel et al., 1988). In this paper, we use an inhomogeneous model to analyse contour maps of the intensity. This model is similar to the Dulk and Dennis (1982) model. But it is slightly different from their model. In the Dulk and Dennis model, the angle \( \theta \) between the magnetic field direction and the line of sight is constant. However, in the present model, the direction of the magnetic field is radial, while \( \theta \) is variable. In addition, we estimate magnetic fields from contour maps of the polarization degree of the 1992 October 27 solar radio burst.

OBSERVATIONAL DATA

The flare of 1992 October 27 occurred at S25 W17, and was classified as M1.1 in soft X-rays and 1 B in Hα (Solar Geophysical Data, 1993). The time profiles in microwaves (Takakura, 1998) and X-rays are shown in Figure 1 (Takakura et al., 1994). We can estimate the photon spectral index \( \gamma_p \) based on the ratio of brightness (count s⁻¹ pixel⁻¹) (Takakura et al., 1994, Kosugi et al., 1995) and the radio spectral index \( \alpha_r \) based on the flux densities at 17 and 35 GHz. The variations of \( \gamma_p \) and \( \alpha_r \) with time are shown in Figure 2. The burst was observed simultaneously with the hard X-ray telescope on board Yohkoh and with the Nobeyama Radioheliograph. Figure 3
shows radio contour maps of polarization degree, \((R-L)/(R+L)\), (R and L are right and left handed polarization, respectively) at 01:44:59.889 (a) and 01:45:29.889 UT (b) at 17 GHz. Figure 4 shows X-ray contour maps and a radio map at 17 GHz at 01:45:27 UT, as well as a radio map at 01:45:29.889 UT. Due to the large beam width, 18" FWHM, the brightness temperatures of radio maps were decreased by a factor of 20.

**ESTIMATE OF THE BRIGHTNESS TEMPERATURE** \(T_b(\rho)\)

The variation of magnetic field and nonthermal electron density with radial distance, \(r\), from the center of the source were assumed to be

\[
B(r) = B_0 \left( \frac{r}{r_0} \right)^{-\alpha_B},
\]

\(1\)

Fig.1. Time profiles of the 1992 October 27 burst in X-rays and microwaves (courtesy of T. Takakura).

Fig.2. Variations of \(\alpha_B\), \(\gamma_e\) and \(\alpha_i\) with time

Fig.3. Contour maps of polarization degree \((R-L)/(R+L)\) (a) at 01:44:29.889 UT. (b) 01:45:29.889 UT. Dashed: left handed; solid: right handed (after Takakura et al., 1994), solid curve in the upper part of (b) is the magnetic neutral line.
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Estimate of Coronal Magnetic

where $B_m$ and $N_m$ are magnetic field strength and electron number density in the innermost core of the source, i.e., at $r = r_m$: the direction of the magnetic field was assumed to be radial. $\alpha_n = \alpha_n$ is taken in the following estimates.

The differential optical thickness for self-absorption can be approximately by (Dulk and Dennis, 1982)

$$d\tau_f = 1.4 \times 10^{-10} \frac{1.30 + 0.98\delta_e}{0.30 + 0.98\delta_e} (\sin \theta)^{-0.09 + 0.72\delta_e} \left( \frac{f}{f_B} \right)^{1.30 - 0.98\delta_e} \frac{N_e(r)}{B(r)} ds,$$

where $\theta$ denotes the angle between the magnetic field direction and the line of sight, $f$ and $f_B$ the frequency and magnetic gyro-frequency, $\delta_e$ the electron energy spectral index and $\rho$ the distance displaced from the project center of the spherical source. After integration, expression (3) became

$$\tau_f = C \left[ \frac{r^2}{r_m^2} \right]^{1/2} ds$$

$$k_1 = \left[ \alpha_n (0.30 + 0.98\delta_e) + \alpha_n + 0.72\delta_e - 1.09 \right]^{-1}$$

$$C_1 = 1.4 \times 10^{-9} \left[ \frac{f}{2.8 \times 10^6} \right]^{1.30 - 0.98\delta_e} \left( \frac{r_m}{\rho} \right)^{0.72\delta_e + 0.09} N_m B_m^{0.30 + 0.98\delta_e},$$

where $r_f (\rho)$ is the radius of $\tau_f \approx 1$. At any given frequency for $\tau_f \gg 1$ in the optically thick regime the radiation will come almost entirely from a thin layer near $\tau_f \approx 1$. Similar to the Dulk and Dennis (1982) derivation, in the present case, the low frequency spectral index is given by

$$\alpha_1 = \frac{1.30 + 0.98\delta_e}{\alpha_n (0.30 + 0.98\delta_e) + \alpha_n + 0.72\delta_e - 1.09}$$

$$\cdot \left[ 2.36 + 0.06\delta_e + \alpha_n (0.50 + 0.085\delta_e) \right].$$
The brightness temperature $T_b(\rho)$ as a function of distance $\rho$ is given by

$$T_b(\rho) = \int_0^{\pi/2} T_{bg} e^{-\tau_\rho} d\tau_\rho,$$

where $T_{bg}$ is given by Equation 37 in the Dulk (1985) paper, and $\tau_\rho = 0$ at $S = S_{max}$. Firstly, we estimate $\alpha_\mu$ according to the expression (5), where $\alpha_\gamma$ are known from the observation (see Figure 2) and the spectral indices $\delta_\mu$ for the electron energies are given by $\delta_\mu = \gamma_\mu + 1.5$ for a thick target. The computed values of $\alpha_\mu$ are also shown in Figure 2.

Then, we estimate the variations of $T_b(\rho)$ with $\rho$ (averaged over 8 directions) at 01:45:29.889 UT according to Eq. (6) and the calculated curves are shown in Figures 5–6. In Figure 5, the calculated curves are for a fixed value of $N_m = 6 \times 10^6 \text{cm}^{-3}$ and two variable parameters ($\alpha_\mu$, $r_m$). In Figure 6, the calculated curves are for two fixed values of $\alpha_\mu = 2$ and $r_m = 2.5 \times 10^8 \text{cm}$ and for a variable parameters ($N_m(\rho)$).

**ESTIMATE OF CORONAL MAGNETIC FIELDS FROM POLARIZATION INVERSION**

It can be seen from Figure 3 that the minimum polarization degrees reached -0.83 at 01:44:59.889 UT and -0.79 at 01:45:29.889 UT in the L-sense, which correspond to the extraordinary wave. Such high polarization degrees may be caused by polarization reversal ("limit polarization"), which has been pointed out by Takakura et al. (1994).

According to Bandiera (1982), in the magnetic dipole assumption (the dipole axis is $x$ axis, $z$ axis is the vertical axis), the magnetic field $B$ and the wave coupling coefficient $C$ (Bandiera, 1982) are given by

$$B = \frac{d(1 + 4\eta^2)^{3/2}}{z^5(1 + \eta^2)^{3/2}},$$

$$C = \frac{z^8\eta(1 + 2\eta^2)(1 + \eta^2)^{3/2}}{\beta(1 + 4\eta^2)^3},$$

where $\eta$ is the ratio of $\nu$ to $\nu_0$.
Estimate of Coronal Magnetic Field

\[ \eta = \left( -3 + (9 + 8 + \tan^2 \theta) \right)^{3/2} / (4 \tan \theta), \]

\[ \beta = \left[ \frac{N \eta^7}{6 \omega \omega^*} \right]^{1/8}, \]

\[ \alpha = 3.06 \times 10^{-21}. \]  

where \( \theta \) is the angle between the wave propagation sense and the \( z \) axis, \( d \) the dipole moment, and \( N \) the electron density. The circular polarization degree of the outgoing wave passing through the quasi-transverse layer (Bandiera, 1982) is

\[ \rho_c = -1 + 2 \exp[-\ln 2/C]. \]  

The apparent distance of the depolarization point measured with respect to the position of the dipole is

\[ q = 2 \beta \eta^{7/8} \left( 1 + 2 \eta^2 \right)^{3/16} \left( 1 + 4 \eta^2 \right)^{3/8} \left( 1 + 16 \eta^4 \right)^{1/8}. \]  

As Alissandrakis et al., (1995) pointed out, in the present case, the above equations cannot be applied straightforwardly because the displacement of two neutral lines is not along the center-to-limb direction and we must apply a coordinate transformation. In our case, \( \delta = 54^\circ \). First, we measured the value of \( q \) from Figure 3 and the photospheric vector magnetograms (Wang et al., 1998). It is \( q = 2 \times 10^9 \) cm. From (11), we obtain \( \beta = 1.2 \times 10^3 \) cm. From (9), if we take \( N = 10^8 \) cm\(^3\), we got \( d = 2.5 \times 10^{22} \) cgs units, \( N = 5 \times 10^8 \) cm\(^3\), and \( d = 1.4 \times 10^{22} \) cgs units. Secondly, from Figure 3, we can read the percentage of polarization degree in the contour map. Then from (7), (8) and (10), \( z \) and \( B \) are obtained. The result of this calculation is listed in Table 1 and Table 2.

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<tr>
<th>( \lambda ) (10(^9) cm)</th>
<th>( z ) (10(^9) cm)</th>
<th>( \rho_c )</th>
<th>( B_1 )</th>
<th>( B_2 )</th>
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**DISCUSSION AND CONCLUSIONS**

By use of Equation (5) the derived characterizing magnetic field gradient \( \alpha_s \) for the 1992 October 27 radio microwave burst are about 0.9 - 2.0 (see Figure 2). It shows that the variations of magnetic field during the bursts are not large \( \alpha_s \) at the peak of 17 GHz is about 2, magnetic field strength \( B \) is about 737 G with
$B_m = 2000 \, G$. It is basically consistent with the value of 759 G calculated by Takakura et al., (1994).

Figure 5 shows that the variations of the calculated brightness temperature $T_b$ by Equation (6) in comparison with the observation at the peak. In Figure 5, $T_b$ curves with the same $\alpha_\theta (= 2.0)$ and different $r_m (1.2 \times 10^8, 2.5 \times 10^8, 4.4 \times 10^8 \text{cm})$ depart from each other, and those with the different $\alpha_\theta (= 1.5, 2.0, 2.5)$ and same $r_m (= 2 \times 10^8 \text{cm})$ are near each other. This shows that calculated $T_b$ are sensitive to $r_m$, and not sensitive to $\alpha_\theta$. The curve with $\alpha_\theta = 2$ and $r_m = 2.5 \times 10^8 \text{cm}$ is in agreement with observation. $\alpha_\theta = 2$ is just equal to calculated $\alpha_\theta$ at the peak from Equation (5). Therefore in Figure 6, using $\alpha_\theta = 2$ and $r_m = 2.5 \times 10^8 \text{cm}$ and variable values of $N_0 (\rho)$, the calculated curves are in better agreement with the observed curve. This shows that the central nonthermal electron density in the radio source is more compact.

In the previous section, we obtained a value of magnetic moment $d = 1.4 \times 10^{32} \text{ cgs units (} N = 5 \times 10^8 \text{ cm}^3)\text{ and } d = 2.5 \times 10^{32} \text{ cgs units (} N = 10^8 \text{ cm}^3)$. It is slightly large. This can be used to estimate the magnetic field and height (Table 1 and Table 2). We can see from Table 1 and Table 2 that the magnetic field was $20-30 \, G$ at the height of $1.7 \times 10^{10} - 1.9 \times 10^{10} \text{ cm}$. These results are basically consistent with the result of Kundu and Alissandrakis (1984).

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REFERENCES


