MEASUREMENTS OF THE MAGNETIC FIELD AND THE GRADIENT OF TEMPERATURE IN THE SOLAR ATMOSPHERE ABOVE A FLOCCULUS USING RADIO OBSERVATIONS

V. M. BOGOD

Special Astrophysical Observatory, Pulkovo, Leningrad, U.S.S.R.

and

G. B. GELFREIKH

Main Astronomical Observatory, Pulkovo, Leningrad, U.S.S.R.

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Abstract. Simultaneous observations made at several wavelengths in microwave range using the high spatial resolution of radiotelescope RATAN-600 make it possible to develop methods of measuring the magnetic fields in the solar corona and the chromosphere. In this paper we develop a method of measuring the magnetic fields from thermal bremsstrahlung and demonstrate it, using observations of a flocculus (plage) during August 1–3, 1977. The observations show that the flocculus under investigation possessed bipolar magnetic structure with peak to peak amplitude of magnetic field strength of about 40 G at the level of the upper chromosphere and the transition region (with a r.m.s. error of 5.7 G for favourable conditions). The radio astronomical map of the magnetic field is in agreement with the Mt. Wilson magnetic field map to within the experimental error. It follows that the average longitudinal magnetic field above the flocculus does not drop significantly with height above the photosphere up to the CCTR (chromosphere-corona transition region). An analysis of the spectra of polarized radio emission also gives an opportunity to determine the temperature gradient in the CCTR (which proved to amount to about 1000 K km^{-1} and to follow their variation with height.

1. Introduction

At present the structure and development of the magnetic fields in the solar atmosphere are generally assumed to be the main factors ultimately responsible for all the phenomena of solar activity (see, for example, Kaplan *et al.*, 1977; Stepanjan, 1976).

The field of a new active region emerges, in particular, at the border of a number of supergranules and is followed by a flocculus (plage) where sunspot and flare activity may develop later. Effective study of an active region essentially depends on a variety of methods used for magnetic field measurements. This is the reason why the interest of solar astrophysicists is permanently focussed on the methods of investigations of magnetic fields (Stenflo, 1978).

Optical magnetographs based on Zeeman splitting of spectral lines yield the most comprehensive and reliable data on magnetic fields at the photospheric level. Using the chromospheric lines, however, does not provide a similar level of information. On the other hand, it is just in the chromosphere that microwave radiation originates.

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Big instruments intended for the investigation of solar radio emission and its polarization give an opportunity to develop methods of magnetic field measurements (weak field included) of different solar features in the chromosphere and upper levels of the solar atmosphere.

Radio emission of the quiet Sun and flocculi are well accounted for in terms of thermal bremsstrahlung (see, for example, Zheleznyakov, 1964). In the presense of a magnetic field this emission becomes circularly polarized due to the differences in absorption for ordinary and extraordinary modes of magneto-ionic theory. The interpretation of polarization measurements as thermal bremmsstrahlung of the Sun allows us, in principle, to measure the strength of the magnetic field. As was shown by Gelfreikh (1972), modern radioastronomical observations may yield an accuracy of ≈ 1 G, which is comparable with the accuracy of optical magnetographs.

This paper deals with some provisional measurements of weak magnetic fields of a flocculus using the radiotelescope RATAN-600 (Berlin *et al.*, 1977).

2. Theory

The degree of circular polarization of thermal bremsstrahlung is given by

$$P = (T_{B_e} - T_{B_o})/(T_{B_e} + T_{B_o}) , \tag{1}$$

where T_{B_e}, T_{B_o} are brightness temperatures for extraordinary and ordinary modes respectively (their expressions are considered below). Here the limiting polarization (see Zheleznyakov, 1977) is assumed to be circular. The brightness temperature is determined by

$$T_B(f, f_H, \alpha) = \int_0^\infty T(l) \exp[-\tau_j(f, f_H, \alpha, l)] \, \mathrm{d}\tau(l, f_H, \alpha), \tag{2}$$

where

$$\tau_j = \int_0^l \varkappa \, \mathrm{d}l'$$

and

$$\tau_j(l, f_H, \alpha) = \int_0^l \varkappa_j[N(l), T(l), f_H(l), \alpha(l)] \, \mathrm{d}l' . \tag{3}$$

$N(l)$ and $T(l)$ are the distributions of electron density and temperature along the line of sight. The parameters of the magnetic field, the gyrofrequency f_H and the angle α between the magnetic vector and the line of sight, also can vary along the line of sight. These values, however, are considered here as constants (homogeneous field). The indexes $j = e$ and o refer to the extraordinary and ordinary modes respectively.

One can write Equation (4) for the absorption coefficient provided that

(i) $f \gg f_0 = (Ne^2/\pi m)^{1/2}, \qquad f \gg f_H,$

(ii) $n_j = 1$ for most angles α,

(iii) the quasi-longitudinal approximation is solid,

$$\varkappa_{e,o} = \zeta N^2 T^{-3/2} (f \mp f_H \, |\cos \alpha|)^{-2}, \tag{4}$$

where ζ is weakly dependent on parameters N and T. Equation (4) is similar to those in the absence of the field if one substitutes $f \to f - f_H \, |\cos \alpha|$ for the extraordinary mode and $f \to f + f_H \, |\cos \alpha|$ for the ordinary one. Then it follows that brightness temperatures must have the following dependence on f and f_H:

$$T_{B_e}(f, f_H, \alpha) = T_B(f - f_H \, |\cos \alpha|), \quad T_{B_o}(f, f_H, \alpha) = T_B(f + f_H \, |\cos \alpha|), \tag{5}$$

where $T_B(f)$ is an imaginary brightness temperature for a physical region with the same distributions of density $N(l)$ and kinetic temperature $T(l)$ but in the absence of a magnetic field. So the brightness temperature spectra for two orthogonal circular polarizations are expected to have similar curves as functions of frequency but with a shift along the absciss by $2f_H \, |\cos \alpha|$. This was pointed out by Soboleva, who suggested using it for determining the magnetic fields in coronal condensations (Korol'kov *et al.*, 1960), the latter being considered as the main source of the S-component radioemission. Later it was proved, however, that in the solar corona at frequencies $f = Sf_H$ ($S = 1, 2, 3, 4$) cyclotron emission and absorption play an important role (Zheleznyakov, 1962). This suggests that relation (5) may be used only for $f \gtrsim 4f_H$.

On the other hand, relation (5) may be given a more suitable differential form (Gelfreikh, 1972) using the series:

$$\begin{aligned} T_{B_e} &\simeq T_B(f) - f_H \, |\cos \alpha| \partial T_B/\partial f + \tfrac{1}{2} f_H^2 \cos^2 \alpha \; \partial^2 T_B/\partial f^2 \,, \\ T_{B_o} &\simeq T_B(f) + f_H \, |\cos \alpha| \partial T_B/\partial f + \tfrac{1}{2} f_H^2 \cos^2 \alpha \; \partial^2 T_B/\partial f^2 \,. \end{aligned} \tag{6}$$

Substituting these in formula (1) for the degree of polarization one gets

$$P = -2 f_H \, |\cos \alpha| \partial T_B/\partial f (2 T_B + f_H^2 \cos^2 \alpha \; \partial^2 T_B/\partial f^2)^{-1}, \tag{7}$$

or neglecting the squares,

$$P = -f_H \, |\cos \alpha| (\partial T_B/\partial f) T_B^{-1} \tag{8}$$

Here, T_B is a good approximation for mean value of brightness temperatures in the two orthogonal polarizations. If we determine the logarithmic spectral index by

$$n = \partial \lg T_B / \partial \lg f = -(\partial T_B/\partial f) f T_B^{-1}, \tag{9}$$

and assume the case of a power spectra $T_B \sim f^{-n}$, then

$$P = n f_H \, |\cos \alpha| f^{-1}. \tag{10}$$

The well-known particular of this relation for optically thin layer results in

$$P = 2f_H\,|\cos\alpha|\,f^{-1} \tag{11}$$

as then

$$T_B = T_T \sim N^2 T^{-1/2} f^{-2}\,.$$

The measurements of magnetic fields using relation (10) do not need measurements of the spectral curves for two polarizations but demand measurements of intensity I, polarization V (at least at one frequency) and spectral index n. In fact, however, only two parameters are needed to measure the magnetic field: The difference temperatures for two types of circular polarizations and the difference in brightness temperatures for two close frequencies:

$$\Delta T_B = T_B(f_2) - T_B(f_1)\,. \tag{12}$$

Using (6) we obtain

$$T_{B_e} - T_{B_o} = -2f_H\,|\cos\alpha|\,\partial T_B/\partial f\,, \tag{13}$$

hence

$$f_H\,|\cos\alpha| = -\tfrac{1}{2}(T_{B_e} - T_{B_o})(\Delta T_B/\Delta f)^{-1} \tag{14}$$

and at last (having in mind that $f_H = 2.8H$)

$$H_l = -V/5.6(\Delta T_B/\Delta f)\,. \tag{15}$$

Here $V = T_B^R - T_B^L$, where R refers to right-handed and L to left-handed circular polarization, positive H_l means the direction of the magnetic field is toward the observer. Note that, in general, $\Delta T_B/\Delta f < 0$ because T increases with height; in this case $T_B^R > T_B^L$ implies a field toward the observer. However, if T decreases with height the polarization is reversed.

Relation (10) used for the determination of the magnetic field strength is to be rewritten like this:

$$H_l \approx 107P(n\lambda)^{-1}\,, \tag{16}$$

where P is the degree of circular polarization (per cent) ($P > 0$ for the excess of right-handed mode, λ is the wavelength (cm), n is the spectral index (see formula (9)).

The formulae above were used for measuring the magnetic field of a flocculus area using regular observations of the Sun with RATAN-600. It is worth mentioning that an attempt to measure the magnetic field by a similar method was made earlier (by Gelfreikh *et al.*, 1975) using solar eclipse observations.

3. Observations and Methods of Their Reduction

The observations of a flocculus made during August 1–3, 1977, were chosen for consideration. This flocculus was observed in the north–east part of the solar disk

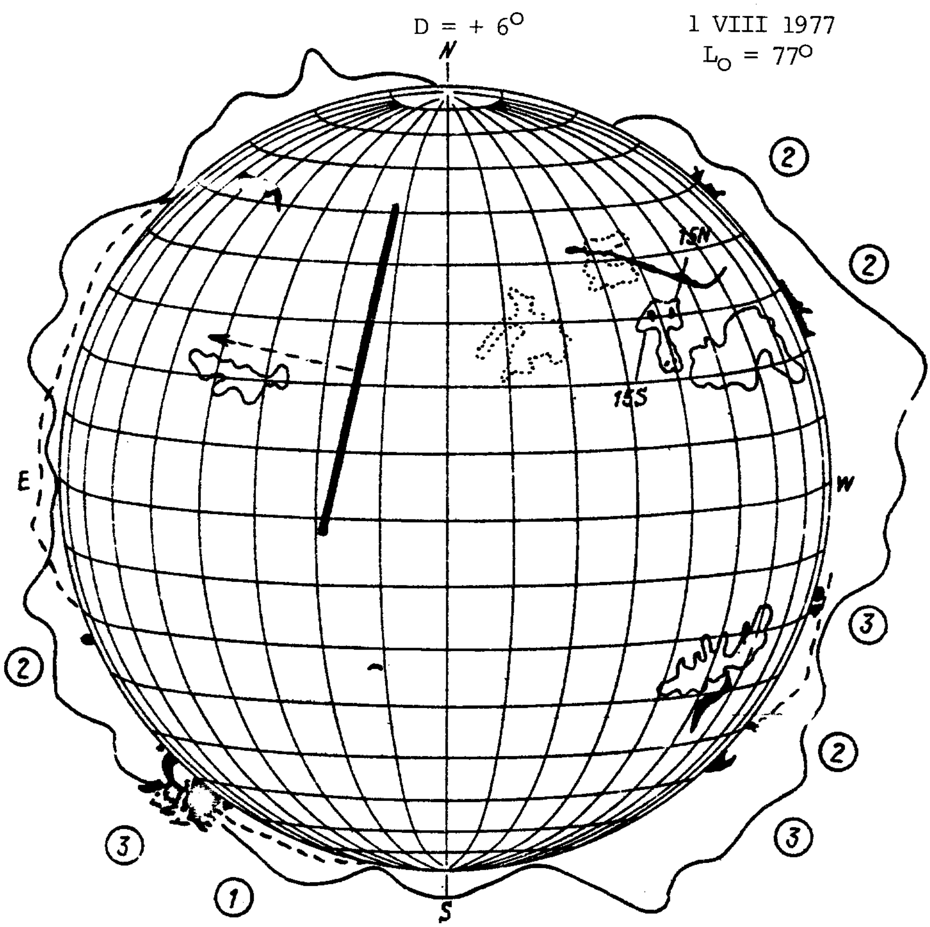

Fig. 1. Map of the Sun with the flocculus position for August 1, 1977. The position of the half-power diagram of the radiotelescope at wavelength $\lambda = 2.0$ cm on the disk and the positions of scanning are shown.

(Figure 1). Figure 1 also shows the position of the flocculus, the h.p.w. of the pattern of the diagram for $\lambda = 2.0$ cm and the direction of scanning. The observations were carried out using the periscope (flat mirror) with the south part of the circular reflector of RATAN-600. The records were made simultaneously with 5 radiometers in the range from 2 to 4 cm, two Stokes' parameters (intensity and circular polarization) being measured. Angular resolutions at wavelength 2.0, 2.3, 2.7, 3.2, and 4.0 cm are in horizontal direction 17″, 19.5″, 24″, 27″.3, 34″.2, respectively and in the vertical direction 13′.8, 15′.6, 18′.4, 21′.6, 25′.4, respectively.

The input feed horns at different wavelengths are displaced with respect to the focus at a distance not exceeding 2.6λ. As a result the source of emission passes sequentially through the 5 frequencies.

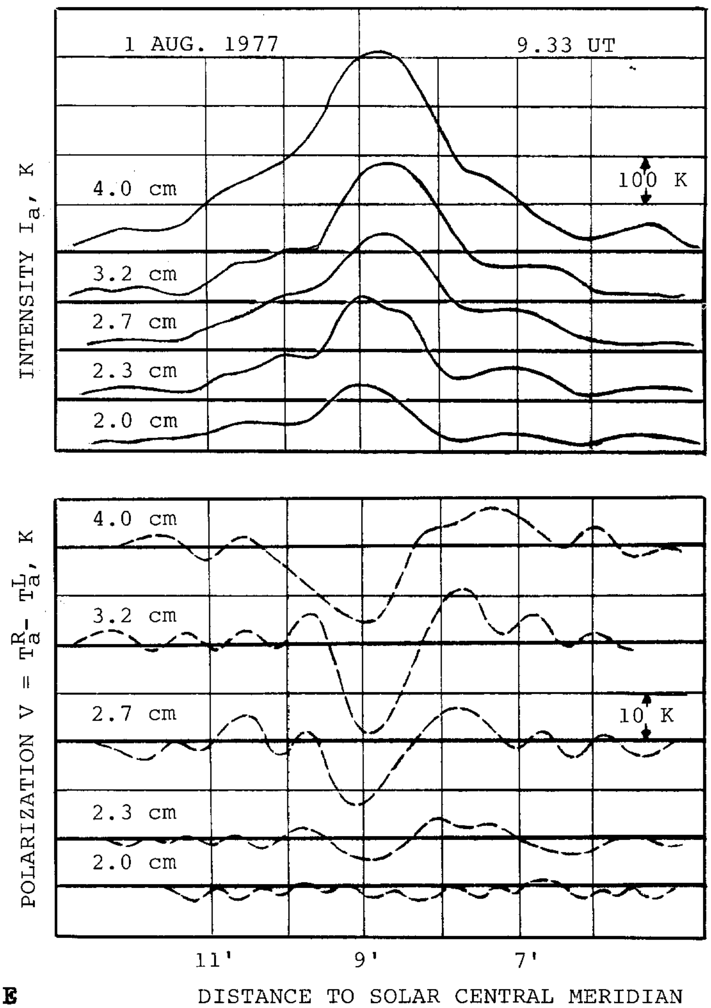

Fig. 2. An example of the records of scanning the flocculus at 5 wavelengths for two Stokes' parameters I and V (intensity and circular polarization).

An example of records of a flocculus taken on August 1, 1977 is shown in Figure 2. These records were processed to eliminate distortion due to aberration and to reduce the registration to a single focus with the help of a computer. To use formula (15) it is necessary to determine the brightness temperatures of polarized and unpolarized components of the flocculus. For calibration a number of observations of the Moon and Tau A were made to secure the necessary parameters of the antenna, i.e. the gain, the scattering coefficient and the vertical diagram pattern.

The contrast of the flocculus on the records is reduced relative to the level of the quiet Sun because the vertical diagram pattern θ_P exceeds several times the vertical size of the flocculus θ_F. This effect must be taken into account when determining the brightness temperature of the flocculus. The vertical size of the flocculus was taken to be $\theta_F \approx 2$ arc min for each day of observation, corresponding approximately to the size of the flocculus area according to optical data. The calculation of the magnetic field was made using the following formula, where all the necessary corrections were taken into account:

$$H_l = T_a^V L_K (L_1 T_{a_1}^Q - L_2 T_{a_2}^Q + L_3 T_{a_1}^F - L_4 T_{a_2}^F)^{-1} . \tag{17}$$

Here, L_1 and L_2 are the correction coefficients, taking into account the scattering of the antenna at frequencies 1 and 2 measured by the observation of the Moon; $L_3 = L_1 \theta_P / \theta_F$ and $L_4 = L_2 \theta_P / \theta_F$ are the coefficients, taking into account both the scattering and the ratio of the vertical sizes of the pattern and the flocculus; L_k is the same, where $k = 3$ or 4. $T_{a_1}^Q$ and $T_{a_2}^Q$ are the antenna temperatures of the quiet Sun; $T_{a_1}^F$ and $T_{a_2}^F$ are the antenna temperatures of the emission due to the flocculus and T_a^V the same but in circular polarization.

For each wavelength the mean magnetic field was calculated for two slopes of the spectrum which were found using the longer and shorter neighbouring wavelengths. The distribution of the magnetic field along the flocculus and the comparison with Hα maps of the Sun are shown in Figures 3, 4 and 5. In addition, the Mt. Wilson maps of the magnetic field in the same scale are given for August 2 and 3.

A comparison of radio and optical data presented above shows the following:

(1) There is a good coordinate agreement between radio and optical features of the flocculus field.

(2) The magnitudes of the magnetic fields measured by radio and optical methods are in reasonable agreement within the experimental error.*

(3) The flocculus is a bipolar structure identical on both radio and optical pictures. (The right circularly polarized radio emission of the flocculus corresponds to the north polarity of the magnetic field in optics. It is consistent with an excess of extraordinary mode of emission.)

Unfortunately, a large difference in time between optical and radio observations (about 9.5 hr) and a long time required for obtaining the magnetic map (about 1.5 hr) in optics reduce the accuracy of comparison to about 15 arc sec.

The errors of the measurement of H by the proposed method can be divided into random and systematic.

A random error is due to noise fluctuations of the receiver together with a strong signal of the quiet Sun. One can write the following expression for the degree of polarization:

$$\delta P = \delta T_S / T_S = (\tau \Delta f)^{-1/2} , \tag{18}$$

where T_S is the noise temperature of the receiver system while observing the solar disk. The latter is the case when the size of the sources exceeds the size of the antenna pattern $\theta_F > \theta_P$ (in both coordinates). When observing the sources on the disk of the

* The total error of comparison connected with uncertainty of the Mt. Wilson magnetograph correction factor and with experimental errors of radiomethod is estimated as a factor of about two.

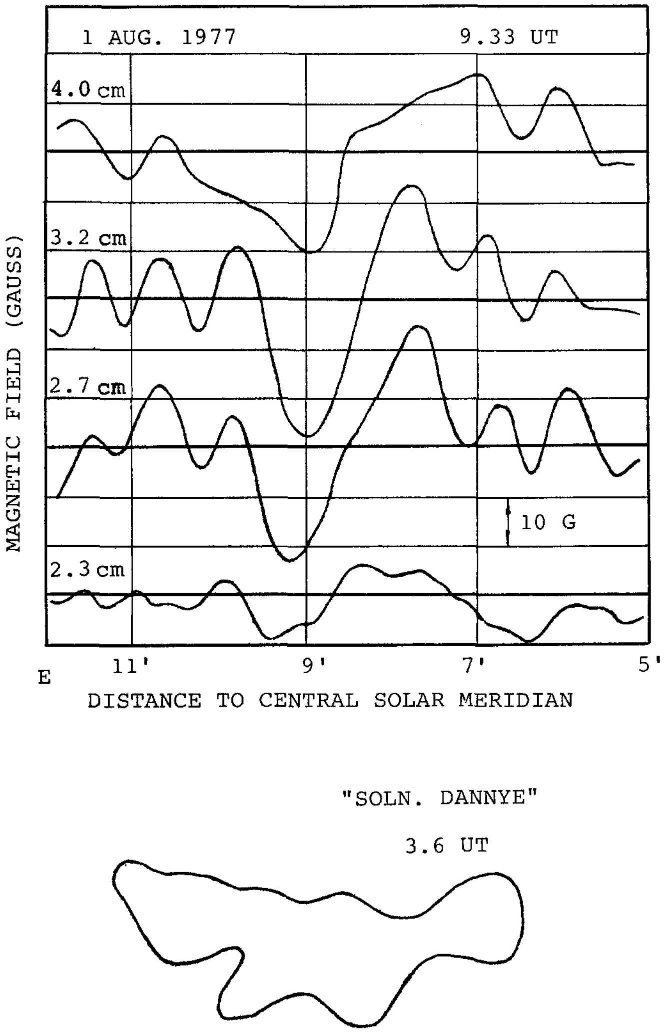

Fig. 3. One-dimensional distribution of the magnetic field across the flocculus on August 1, 1977. Vertical size of the flocculus was assumed to equal 2 arc min in accordance with the optical size of the flocculus field in Hα. North polarity of magnetic field is shown in upwards direction. Configuration of the flocculus field is shown at the bottom.

Sun with dimensions $\theta_F < \theta_P$ the error of polarizations measurements increases by a factor of θ_P/θ_F. The r.m.s. errors of the magnetic field for each λ are given in Table I. One can see that the error of H increases with decreasing (this is also connected with decrease of the spectral index n) and it equals the magnetic field at the wavelength $\lambda = 2$ cm.

The systematic errors are due to a number of factors:

(1) Accuracy of separation of the quiet Sun level. In our measurements the level of the quiet Sun is determined as the lowest envelope on superimposed records for both

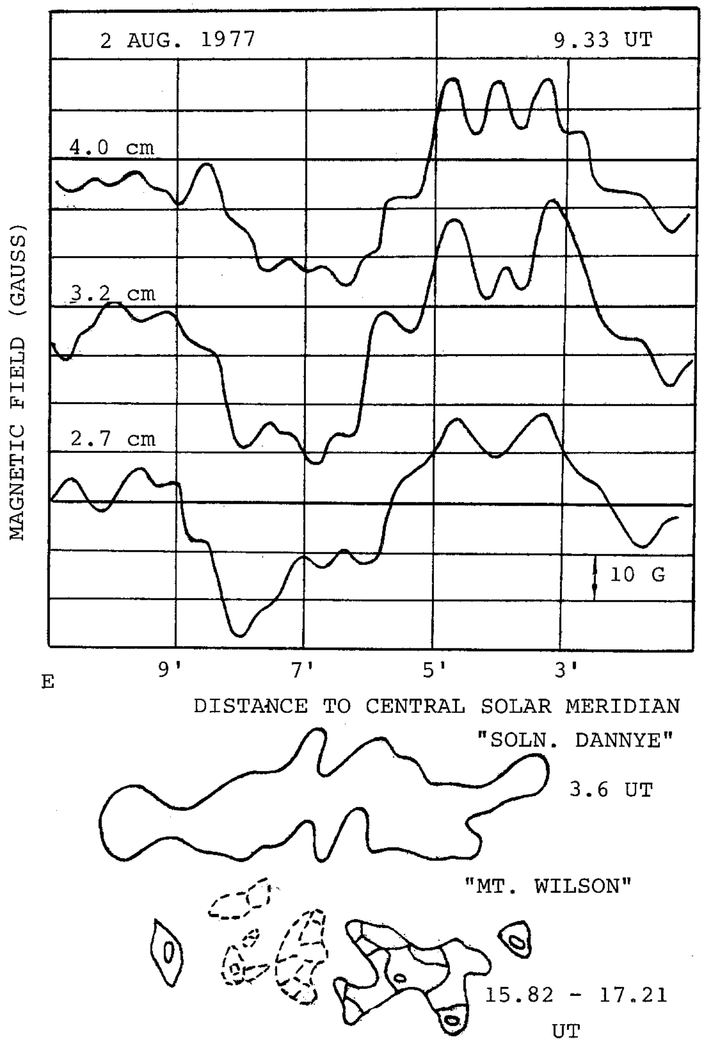

Fig. 4. The same as Figure 3 for August 2, 1977. In addition, the Mt. Wilson map of the magnetic field is given. Here, solid line is plus, dotted line is minus. Levels: ±5, ±10, ±20, ±40, ±80. Coincidence of the signs of magnetic fields obtained by radio and optical methods are shown. There is some coordinate uncertainty of about 15 arc sec while comparing optical and radio images.

August 1, 2, 3 and July 31, 1977. The latter was taken on the day with minimum activity of the Sun. The error of separation of the quiet Sun level is about 1% of the full signal, and the error of separation of excess of emission due to flocculus (of the order of 20%) may result in two-fold flux excess error. This error can be reduced by increasing the contrast of the radio image. This might be possible when using an instrument with high two-dimensional resolution or using a device which measures the slope by a differential method (see Bogod and Gelfreikh, 1974; and Gelfreikh *et al.*, 1975).

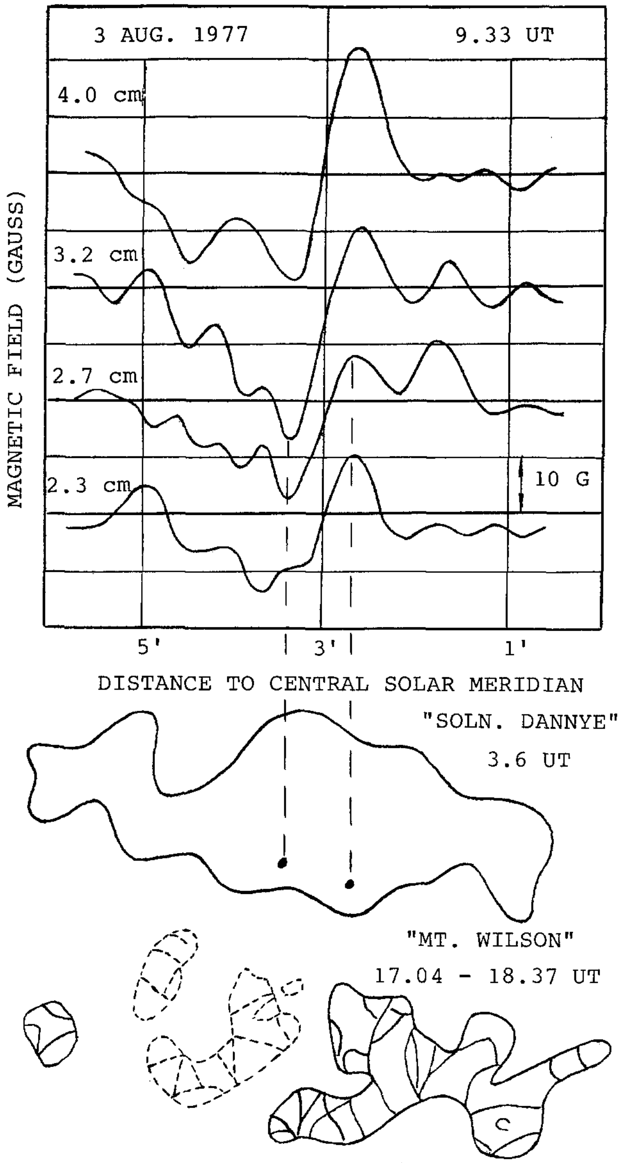

Fig. 5. The same for August 3, 1977. The appearance of two pores on optical images have presumably resulted in strengthening two corresponding maxima at the radio magnetic maps as indicated in the figure.

(2) Instrumental defects of measurements of a very weak circularly polarized signal (see Korzhavin, 1976). These defects are of varying nature and they can be divided into two groups: (i) small-scale changes of polarization signal of the order of θ_P when observing a source with $\theta_P \leqslant \theta_{PX}$. The magnitude of this signal is approximately $\pm 1.5\%$ of the general signal in channel I (intensity); (ii) large-scale changes of about $\theta_\odot$ (size of the solar disk).

TABLE I

The r.m.s. errors of the magnetic field at different wavelengths

wavelength, cm	4.0	3.2	2.7	2.3	2.0
r.m.s. deviation of the field averaged along the diagram of the antenna, gauss	0.6	0.8	1.2	2.2	9.3
r.m.s. deviation of the field averaged over the vertical section of the flocculus, gauss	5.7	8.0	10.8	18.8	65

Both the low contrast on the record and a comparatively large size of the source ($\theta_F > \theta_P$) result in the low value of the small-scale effect while observing weak and extended flocculus. Large-scale changes are eliminated empirically using a set of records of the quiet Sun in the V-channel for a number of days. Such a drawing of the zero line in the V-channel is similar to the standard procedure of separation of the quiet Sun level in the channel of intensity.

4. Discussion

Similar to any other magnetographic method the measurements of magnetic fields described above give the value of magnetic fields averaged over a certain volume with a corresponding weight function. As far as the averaging in the plane of the image is concerned it is made over the surface of the Sun with the weight function determined by the diagram pattern of the antenna. The latter at the mean frequency of our observations was $24'' \times 18'.4$.

We have altered this averaging by means of referring the whole flux of the magnetic field to a smaller area with the height equal to the size of the flocculus field in the diagram. This resulted in increasing the value of the magnetic field strength by an order of magnitude and made it nearer to the value of optical measurements made with a resolution of $9''.5 \times 12''.6$.

Note, however, that the flocculi are known to have a fine structure, and an increase of the resolution in optical observations results in greater magnetic field strengths. In these measurements such elements are averaged over the area of the diagram of the antenna. If we referred the polarized flux to the size of the smallest elements the resulting magnetic field would certainly increase by an order of magnitude.

Another important problem for radioastronomical measurements of the magnetic field is the averaging of the field along the line of sight; that is the problem of the length of the region of generation and its height above the photosphere.

Let us consider Equation (15). The numerator is Stokes' parameter V, its value being due to the effect of the magnetic field in all the radiating regions in the line of sight, and is generally a function of a small parameter $y = \delta f/f$, where $\delta f = f_H \,|\cos \alpha|$. The denominator is a parameter of the slope of the spectrum and is also a function of a small argument $y = \delta f/f$, where $\delta f = \Delta f$. One can obtain the following expression for brightness temperature where the second and higher powers of y are neglected:

$$T_B(f+\Delta f) = T_B(f) + 2\int_0^\infty T(l)\exp[-\tau(l,f)] \times \times\left[y(l) - \int_0^l \varkappa(l',f)y(l')\,dl'\right]\varkappa(l,f)\,dl. \tag{19}$$

For the denominator of Equation (15), y is a parameter of the equipment independent of f_H. Using representation (19) for formula (15) we can write:

$$H_l = \frac{\int_0^\infty T(l)\exp[-\tau(l,f)][H_l(l') - \int_0^l H_l(l')\varkappa(l',f)\,dl']\varkappa(l,f)\,dl}{y\int_0^\infty T(\tau,f)\,e^{-\tau}(1-\tau)\,d\tau} \tag{20}$$

which allows us to follow the averaging of the magnetic field.

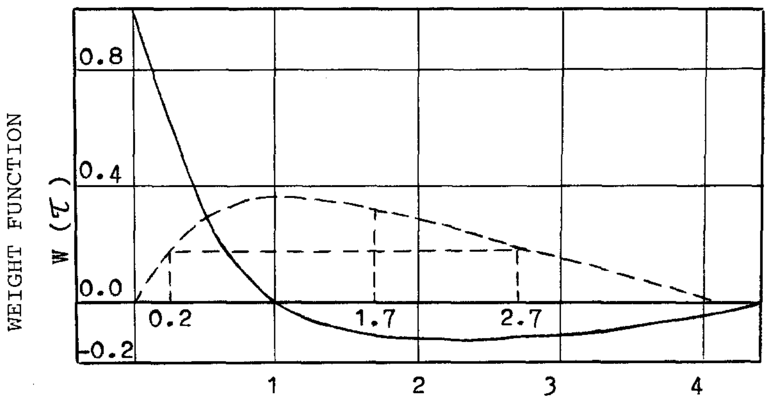

Fig. 6. The weight functions $(1-\tau)e^{-\tau}$ (solid line) and $\tau e^{-\tau}$ (dotted line) used for the calculations of the mean values of temperature and its gradient.

Note that in an isothermal layer both the numerator and the denominator become zero, which excludes the possibility of measuring the field. Figure 6 represents the weight function for $T(\tau)$ in computing the denominator. Another form of the denominator may be found by integration by parts, which results in

$$\int_0^\infty T(\tau)\,e^{-\tau}(1-\tau)\,d\tau = -\int_0^\infty (\partial T/\partial\tau)\tau\,e^{-\tau}\,d\tau = -\partial\tilde{T}/\partial\tau. \tag{21}$$

The mean value of $\partial\tilde{T}/\partial\tau$ has a physical meaning because the corresponding weight function (see Figure 6) is always positive. Its width at the 50% level is

$\tau = 0.2$–2.7 and the median is at $\tau_m = 1.7$; to the latter we shall refer the value of the derivative. So

$$\partial T/\partial l = \frac{\partial T(l_m)/\partial l}{\varkappa(l_m, f)} = \frac{T^{3/2} f^2 \, \mathrm{d}T(l_m)/\mathrm{d}l}{\zeta N^2(l_m)}, \tag{22}$$

where assuming $T_B \simeq T(\tau_m)$ one obtains for (9)

$$n = \left(\frac{T_B^{1/2} f^2}{\zeta N^2(l_m)}\right)\left(\frac{\mathrm{d}T(l_m)}{\mathrm{d}l}\right). \tag{23}$$

Consequently, for the degree of polarization in a uniform magnetic field we have

$$P = \left(\frac{T_B^{1/2} f f_H}{\zeta N^2(l_m)}\right)\left(\frac{\mathrm{d}T(l_m)}{\mathrm{d}l}\right). \tag{24}$$

This case differs from that of optically thin layer by a possible growth of the degree of polarization with frequency. This possibility is due to the variation of the gradient of temperature while moving to shorter wavelengths. This gradient is, in practice, a difference in temperatures at the distance l at which $\Delta\tau = 1$ (note that l increases with f):

$$\frac{\partial \tilde{T}}{\partial l} = \Delta T|_{\Delta\tau=1}.$$

Because the corona is largely transparent for microwaves, the radioradiation is generally emitted in three regions of the solar atmosphere which significantly differ in their parameters:

- The outer region is the corona with $\tau \ll 1$ and $T \approx 10^6$ K;
- the intermediate region – the CCTR with $\tau \lesssim 1$, $\partial T/\partial l \geq 10^3 \text{ K km}^{-1}$, $10^4 < T < 10^6$ K;
- the interior region of the chromosphere with $\tau \gg 1$, $T \approx 10^4$ K.

Accordingly, the integrals in the formulae above could be approximately considered separately over these regions and simplified taking into account the parameters of each region. In the corona $\tilde{H}_l^{\text{cor}} = c \int H_l(l) N^2(l) \, \mathrm{d}l$, that is, the weight function is simply the second power of electron density and $\Delta H_l^{\text{cor}} = \tilde{H}_l^{\text{cor}} \Delta T^{\text{cor}} / \Delta T_B$, where $\Delta T_B^{\text{cor}} = \tau T$.

The absence of polarization at our shortest wavelength $\lambda = 2.0$ cm suggests that this term is negligible. This may be due to the following reasons: either the magnetic field in the corona drops significantly over one scale height of the decreasing of N^2, or the contribution of the corona ΔT_B^{cor} in the overall value of ΔT_B is small (both factors may be of importance).

In the transition region which is usually considered to be of small thickness (the property generally found from EUV observations) one can propose $H_l = \text{const.}$ and then

$$\Delta H_l^{\text{tr}} = \tilde{H}_l^{\text{tr}} \Delta T_B^{\text{tr}} / \Delta T_B.$$

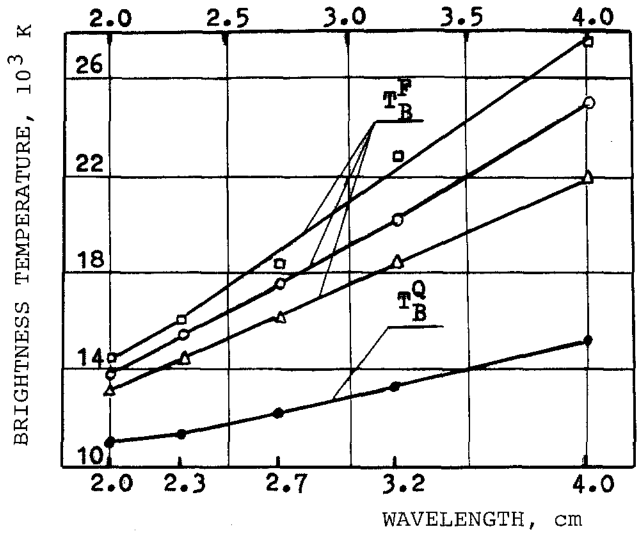

Fig. 7a. The spectra of the brightness temperatures of the quiet Sun (T_B^Q) and of the flocculus (T_B^F). The data are: □ - Aug. 1, △ - Aug. 2, ○ - Aug. 3.

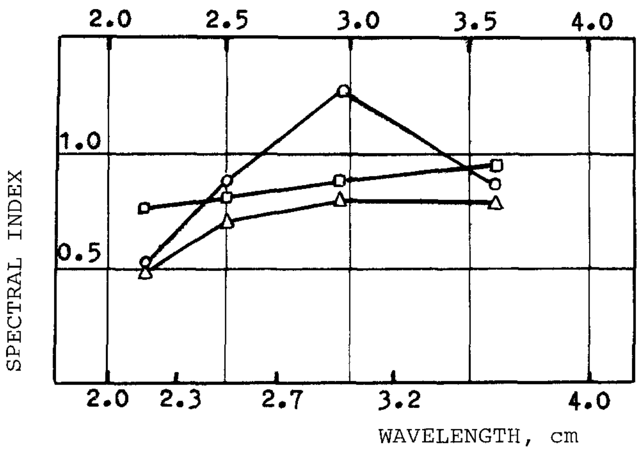

Fig. 7b. Variation of the spectral index depending on wavelength. For all three days there is a tendency for the index to decrease for shorter wavelength.

The optical thickness of this layer could be either large or small depending on the temperature gradient and the wavelength. For the chromosphere we have a similar expression,

$$\Delta H_l^{\text{ch}} = \tilde{H}_l^{\text{ch}} \Delta T_B^{\text{ch}} / \Delta T_B, \quad \text{where} \quad \Delta T_B = T \int e^{-\tau}(1-\tau)\,\mathrm{d}\tau .$$

Here we know with certainty that $\tau \gg 1$ and $\partial T/\partial l$ is generally small.

We now consider the observed data for the flocculus (Figures 7a, b, c, d). First we note that the values of magnetic field found from the wavelengths 2.3–4.0 cm have on

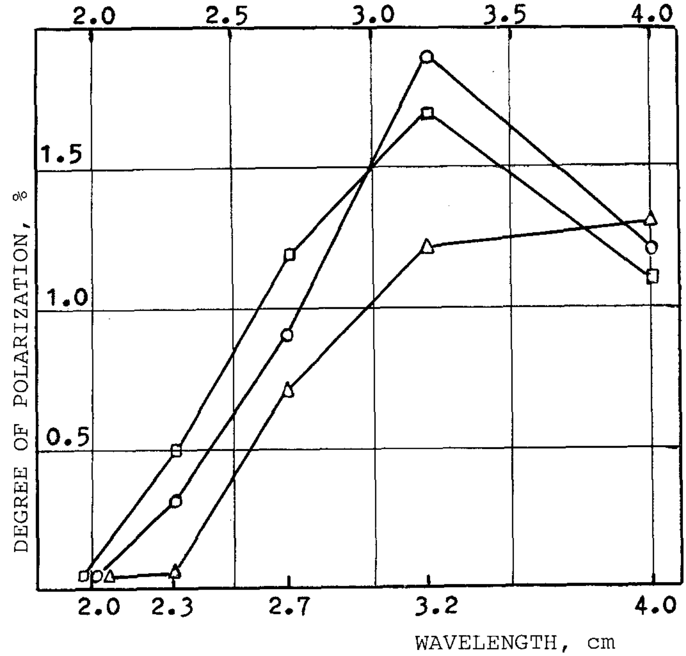

Fig. 7c. The spectra of degree of circular polarization. Note a significant increase of circular polarization degree, up to $\approx 1.5\%$, in the wavelength range from 2 to 3.2 cm.

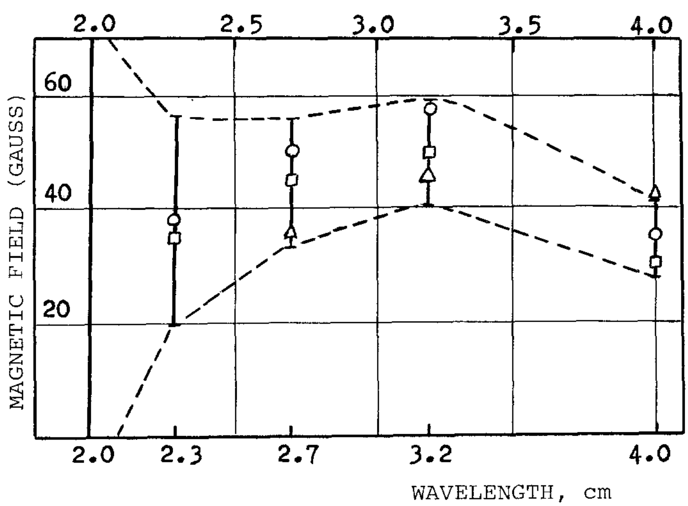

Fig. 7d. Magnetic field strength versus wavelength. The average standard deviations are shown.

the average similar magnitudes which do not differ significantly from the photospheric field (see Figures 4 and 5). It follows that: (i) the gradient of the magnetic field on the scale of the chromosphere is not very large, so assuming the height of the chromosphere equal to 2000 km one gets $dH/dl \approx (5-10) \times 10^{-3}$ G km^{-1}; (ii) the region of emission for all the wavelengths used is not very thick. In particular, even the longest wavelength 4.0 cm is not yet generated in the corona.

Let us consider the spectrum of polarization using formula (24) for an optically thick region. While the values found for the magnetic field are similar at all the wavelengths, the values of the spectral index and the degree of polarization P are changing significantly within the wavelength range. At the shortest wavelength $\lambda = 2.0$ cm the degree of polarization is below the limit of detection because of the limitation imposed by the low temperature gradient $\mathrm{d}T/\mathrm{d}l$. With a certain accuracy we may deduce a relatively low temperature gradient in the chromosphere by considering the emission at this wavelength.

The greatest degree of polarization was found at $\lambda = 3.0$ cm. Assuming $N = 3 \times 10^{10}\ \mathrm{cm}^{-3}$ and $H_l = 40$ G and using relation (24) we obtain $\mathrm{d}T/\mathrm{d}l \approx 1000\ \mathrm{K\ km}^{-1}$. At present such values of the gradient are considered normal for the transition region. Meanwhile the low value of brightness temperature $T_B = 22 \times 10^3$ K shows that the emission is generated in the lower part of the transition region. On the other hand the relatively high temperature $T_B = 15\,000$ K at $\lambda = 2.0$ cm suggests a relatively high mean temperature in the upper chromosphere where the gradients of temperature are much lower.

The dependence of gradient $\mathrm{d}T/\mathrm{d}l$ on wavelength reflecting the dependence on the height above the photosphere is given in Figure 8, the condition $NT = \text{const.}$ being used. The difference of heights where the gradient of T is estimated, using $N = 3 \times 10^{10}\ \mathrm{cm}^{-3}$, is of the order of 10 km between the neighbouring points on the plot. If the electron density is smaller then both these distances and the gradients of temperature should decrease proportionally to N^2.

Note that the polarized flux spectra proved to be a source of information on the gradient of temperature but not on the gradient of the magnetic field. Similar information can be obtained, in principle, from the measurements of spectral index

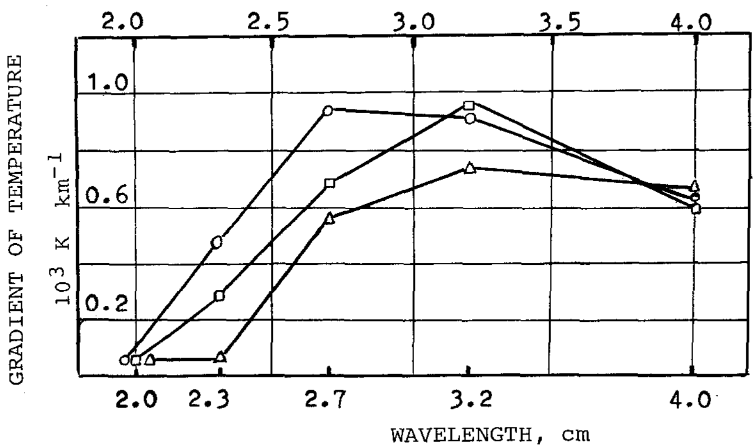

Fig. 8. Gradient of temperature $\partial T/\partial l$ versus wavelength. Effective emission layer for each measured point is only some tens of km using chromosphere parameters like $N = 3 \times 10^{10}\ \mathrm{cm}^{-3}$ and $T = 10^4$ K.

n. The measurements of polarization, however, were differential (by means of modulation) and consequently of higher accuracy. Moreover, they are less dependent on the variations of the diagram pattern, a factor which depends on wavelength.

5. Conclusion

The measurements show that the mean magnetic field of a flocculus does not decrease significantly with height from photospheric values to the level of the CCTR (region with abnormally high gradient of temperature). This is in agreement with the optical measurements by Severny (1966). The spectral analysis of polarized emission allows us to find the gradient of temperatures and their distributions with height above the photosphere. An interesting extension of such investigations may be the expansion of the spectral range observed. On the one hand, the longer wavelengths extend the magnetic field measurements from the level of the CCTR to the lower corona, yielding another value of H_l, i.e. an average magnetic field with weighted function $N^2(l)$.

On the other hand, as one can conclude from formula (24), shorter wavelengths may give us an opportunity to measure H at deeper levels of the chromosphere (the measurable degree of polarization may be due to the dependence $P \sim f_H f$) above sunspots. Here, the gyroresonance emission (up to 4th harmonic) would not affect the degree of polarization.* An important fact is that electron density increases with depth less rapidly than the full concentration of atoms because of the decrease of the degree of ionization. That is why a short wavelength (millimeter range) may be useful in making a magnetic map.

The sensitivity of this method allows us to investigate the magnetic field of the quiet Sun. However, in this case a very extended vertical diagram is not convenient. Here the most important results can be obtained with large diameter fully steerable parabolic antennas.

The observation of circular polarization with the north part of RATAN-600 which has a small vertical diagram allowed the small regions of strong magnetic field to be detected (Bogod, 1978). However, the measurement of a weak magnetic field in the small part of the solar disk is still outside the sensitivity of radio-astronomical technique.

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* An analysis of gyroresonance emission above sunspots has shown that their magnetic field only decreases by some 20% when approaching CCTR.

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