Radiophysics and Quantum Electronics, Vol. 39, Nos. 11–12, 1996

ALTITUDE DISTRIBUTION OF THE MAGNETIC FIELD ABOVE A SUNSPOT BASED ON OPTICAL AND RADIOASTRONOMICAL OBSERVATIONS

V. E. Abramov–Maksimov, V. M. Bogod, V. N. Borovik,
G. F. Vyalshin, V. I. Garaimov, G. B. Gelfreikh,
and V. G. Medar'

UDC 523.98

We present the results of measurements of magnetic fields above a sunspot at different altitudes of the solar atmosphere for a number of observation days. The data are based on simultaneous optical and radio observations in August, 1992. The existence of a maximum in the field intensity at the chromospheric level is confirmed.

1. INTRODUCTION

The detection of strongly polarized sources of enhanced radio emission above sunspots and the interpretation of their emission by the theory of thermal cyclotron radiation [1] allowed us to develop a method for measuring magnetic fields in the transient region between the chromosphere and corona above the spots on the basis of radioastronomic observations of the sun [2]. The method used is based on the determination of the minimum wavelength λ' at which the polarized radiation is recorded. For shorter wavelengths we observe only weak, almost nonpolarized thermal radiation. The estimates of the optical thickness of the radiating region show that the most important contribution to the cyclotron radiation is from an extraordinary wave at the third harmonic and from an ordinary wave at the second harmonic of gyrofrequency [1], which indicates that the strongly polarized radiation at the wave λ' in the range of 2–3 cm is generated in the region in which the magnetic field is described by the formula $H = 3570/\lambda'$ (H in [G] and λ' in [cm]) and is from 1200 to 1800 G.

The combination of radioastronomical measurements with simultaneous optical observations, which allow the measurement of magnetic fields of the spots at the photospheric and chromospheric levels by Zeeman's splitting of spectral lines, considerably improves the possibilities of the study of the structure and distribution of magnetic field intensity with the altitude above the sunspots.

This comparison was carried out in [3–5] in which it is shown that the maximum values of magnetic field are attained at the lower chromosphere rather than at the photospheric level. In this paper we perform a similar study for a large spot based on the results of radioastronomic observations of the sun conducted with the RATAN-600 radio telescope using a new improved equipment that allowed us to determine the magnetic field above the spot at coronal altitudes with a better accuracy (several %).

2. THE RESULTS OF RADIOASTRONOMICAL OBSERVATIONS

For the study we selected group N 255 (according to the bulletin *Solnechnye Dannye*), which passed the disc from August 12 to 14, 1992. During the time it was located on the disc, the active region was a large leading spot with a maximum magnetic field intensity of 3600 G (see *Solnechnye Dannye* No. 8, 1992) with the tail edge in the form of numerous small spots and pores. After passing the central meridian (August 18) we observed a rapid development of the tail edge of the group with a high recorded flare activity (*Solar–*

Main Astronomical Observatory, Russian Academy of Sciences; Special Astrophysical Observatory, Russian Academy of Sciences; Saint Petersburg, Russia. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 39, Nos. 11–12, pp. 1436–1442, November–December, 1996. Original article submitted May 15, 1996.

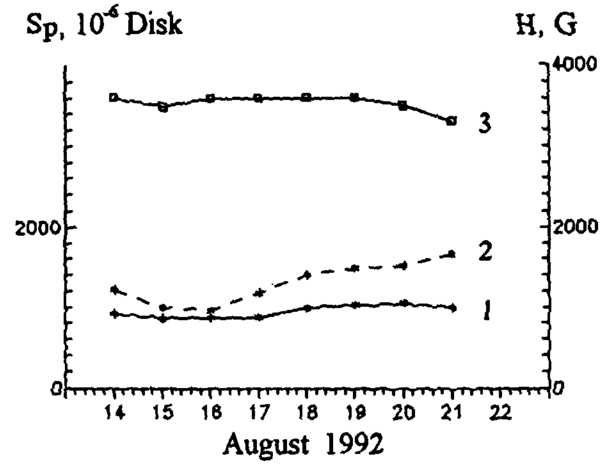

Fig. 1. The optical characteristics of N 255 group according to *Solnechnye Dannye*. 1 is the leading spot area, 2 is the total group area, and 3 is the intensity of magnetic field at the photosphere.

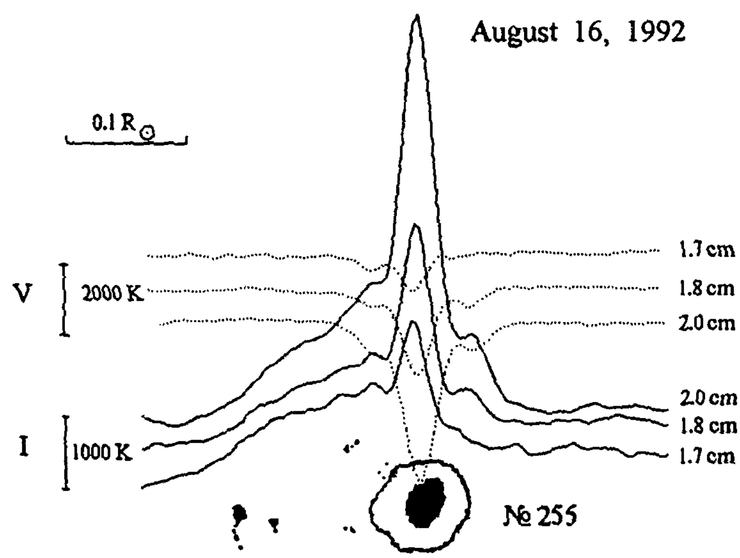

Fig. 2. The N 255 active region and the local source above the latter from RATAN-600 observations.

Geophysical Data). The structure and the area of the leading spot had high stability, which is shown in Fig. 1.

To measure the solar magnetic field by the radio method, we used the RATAN-600 observations performed in August 1992 using a new panoramic spectrum analyzer (PSA) in the range from 1.7 to 31 cm with a 5% frequency resolution for the short-wave part of the spectrum. The observations were carried out once a day in the regime of the sun passing through an immobile directivity pattern of the radio telescope. The pattern width at the half-power level was 17 sec of arc at 2 cm wave in the east-west direction.

An sample record of the local source above the active region is shown in Fig. 2 for several wavelengths with a distinct spot component above the leading spot in the intensity (Stokes "I" parameter) and polarization (Stokes "V" parameter) channels. For wavelengths from 1.7 to 2.0 cm the polarization degree attains 95 to 100%. It must be noted that observing the same active region on the radio heliograph in Nobeyama

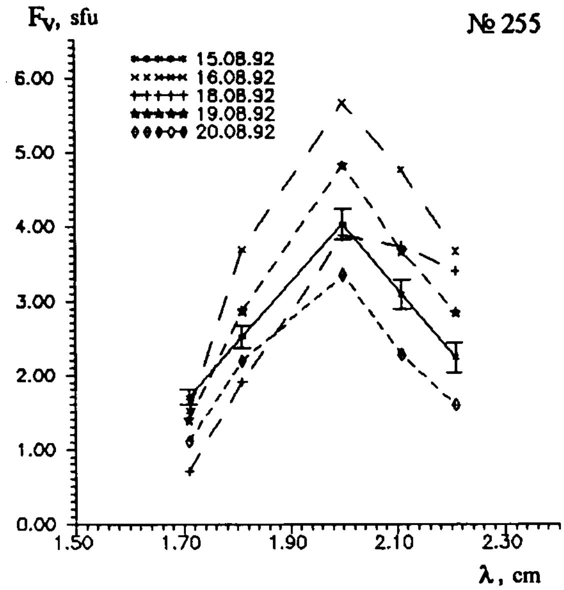

Fig. 3. The spectra of the polarized radio emission from the local source above the leading spot of N 255 group.

Table 1.

Date	H(rad.)	H(opt.)	H(rad.)/H(opt.)
14	2300	3600	0.64
15	2390	3500	0.68
16	2200	3600	0.61
18	2120	3600	0.59
19	2220	3600	0.62
20	2220	3500	0.63

(Japan) at 17 GHz (1.76 cm) a radio source with a 100% circular polarization was recorded above the leading spot of the group [6], which fully corresponds to RATAN-600 observations.

Since at the shortest wave (1.7 cm) for which the RATAN-600 observations were performed in that period the polarized radiation source is observed distinctly, the critical wavelength was found by extrapolating the polarized radiation spectrum to zero. Sample spectra of polarized radiation for this spot are shown in Fig. 3 for several days. The magnetic field intensities (gauss) that correspond to the obtained critical wavelength are given in Table 1 (column 2). The measurement error is below 90 G.

3. COMPARISON OF RESULTS OF RADIO AND OPTICAL OBSERVATIONS

The magnetic fields measured by the radioastronomic method were compared with the results of optical observations from *Solnechnye Dannye* and *Solar–Geophysical Data*:

- in Table 1 column 3 shows the maximum intensities of the magnetic field (gauss) from *Solnechnye Dannye* (CrAO measurements);
- according to *Solar–Geophysical Data*, the values of maximum magnetic field measured over the line of 5250.22 Å FeI at Mt. Wilson station are from 2600 to 3000 G;
- the measurements of magnetic field for this spot over the line of 6302.499 Å FeI performed by G. F. Vyal'shin with the ATSU–5 horizontal solar telescope at Pulkovo observatory on August 13-14 show maximum intensity of the magnetic field from 2800 to 2900 G;

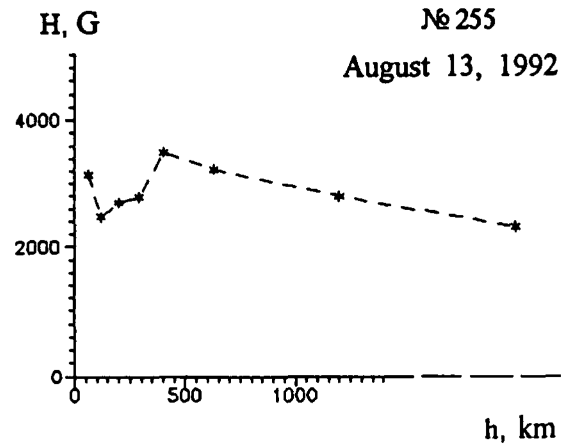

Fig. 4. Altitude distribution of magnetic field above the spot from the results of joint optical and radio observations.

Table 2.

Wavelength	Element	Altitude (km)	H, G
6102.72	Ca I	1200	2800
6108.15	Ni I	400	3300
6111.05	Ni I	60	3150
6119.54	V I	400	3900
6128.99	Ni I	120	2500
6136.99	Fe I	200	2700
6141.72	Ba II	630	3200
6151.63	Fe I	290	2800

- the maximum magnetic field of the same spot measured on August 18 at Mees Solar Observatory is 2800 G [6].

It is evident that the measurements of magnetic field intensity for one and the same spot performed at different stations show great scatter. It is noteworthy that the magnetic field intensity measured by the radio method is about 0.63 of that measured optically (according to *Solnechnye Dannye*). This relationship is somewhat lower than the one obtained previously (see, for example, [2,7]) for a group of spots with complex structure (in these papers the magnetic field values from *Solnechnye Dannye* were used).

For one observation day (August 13) we have the measurements of the magnetic field over several lines for the studied spot of N 255 group. The measurements of magnetic fields of the spots were made by photographing with ATSU-5 horizontal solar telescope at Pulkovo observatory using the Zeeman splitting of spectral lines. Eight spectral lines were used. The altitudes of formation of these lines and the results of magnetic field measurements are given in Table 2.

The magnetic field distribution based on joint optical and radio observations is shown in Fig. 4 in which we present the dependence of the maximum intensity of the magnetic field for each line on its formation altitude. The maximum error of magnetic field measurement by the optical method is below 300 G. We also see the point that corresponds to the magnetic field determined by the radio method (the results of several eclipse observations of the sun indicate that the source of polarized radiation above the spot was located at an altitude that does not exceed 2000 to 3000 km above the photospheric level).

4. DISCUSSION OF RESULTS

As in the previous papers [3–5], for the spot under study we observe the characteristic maximum at effective altitudes from 400 to 700 km. On the other hand, at altitudes from 300 to 400 km we observed an intensity drop (with the subsequent increase). If we assume that the curves obtained reflect the current situation of the field intensity distribution over the altitude, it can be concluded that the magnetic field is enhanced somewhere in the middle chromosphere, which requires the presence of local currents in these layers that surround the tube of force of the spot. The thickness variations in the tube of force are related to the great vertical gradients of the temperature on the photosphere-chromosphere-corona interfaces that are different inside the magnetic tube of force of the spot and outside it in the case of strong thermal insulation of these distributions by the magnetic field of the spot.

It must also be noted that in the case of a strong heating of the corona above the spot or in the presence of fast particles in the tube of force, a contribution to the polarized radiation flux at the fourth harmonic of gyrofrequency is also possible. In this case the obtained value of magnetic field intensity in the corona must be decreased by 25%. Since the values of magnetic field obtained from the optical and radio astronomic data fit the smooth curve in the corona – upper chromosphere region, we conclude that the two methods are correct, which are based on entirely different physical phenomena (Zeeman effect in optics and the cyclotron radiation in the radio-frequency spectrum). Even if the radio measurements of the field in the corona are overestimated because of the disregard of the contribution from radiation at the fourth harmonic of gyrofrequency, the principal conclusion of the paper on the local enhancement of magnetic field in the chromosphere remains valid as it is based on optical measurements. However, we must not rule out the necessity of a more detailed analysis of the estimates of altitudes of optical line generation the results of which we used.

This paper was supported by the Russian Foundation for Fundamental Research (grant No. 94–02–06508), the State Science and Technology Project "Astronomy" (Nos. 4–27, 4–110), and the International Science Foundation (NS8000 and NS8300).

REFERENCES

1. V. V. Zheleznyakov, *Radio Emission of the Sun and Planets* [in Russian], Nauka, Moscow (1964).
2. Sh. B. Akhmedov, V. M. Bogod, G. B. Gelfreikh, and A. N. Korzhavin, *Sol. Phys.*, **79**, 41 (1982).
3. G. B. Gel'freikh, A. N. Koval', and N. N. Stepanyan, In: The Year of the Solar Maximum. Proc. Int. Conf. Issue 2 [in Russian], IZMIRAN, Moscow, 193 (1981).
4. V. M. Bogod, G. F. Vyal'shin, G. B. Gel'freikh, and N. S. Petrova, *Soln. Dannye*, No. 1, 104 (1982).
5. V. E. Abramov–Maksimov, G. F. Vyalshin, G. B. Gelfreikh, and V. I. Shatilov, *Sol. Phys.*, **164**, 333 (1995).
6. K. Shibasaki, et al., *Publ. Astron. Soc. J.*, **46**, 17 (1994).
7. K. R. Lang, R. F. Willson, J. N. Kile, J. Lemen, K. T. Strong, V. M. Bogod, G. B. Gelfreikh, B. I. Ryabov, S. R. Hafizov, V. E. Abramov–Maksimov, and S. V. Tsvetkov, *Astrophys. J.*, **419**, 398 (1993).