Astronomy Letters, Vol. 25, No. 4, 1999, pp. 250–257. Translated from Pis'ma v Astronomicheskii Zhurnal, Vol. 25, No. 4, 1999, pp. 299–307.

First Measurements of the Magnetic Field in a Coronal Hole from RATAN-600 Radio Observations of the Sun

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Received April 3, 1998; in final form, September 11, 1998

Abstract—Based on RATAN-600 spectral–polarization observations of the Sun in the microwave range 2 to 30 cm with a high angular and frequency resolution, we determined the magnetic-field strength in a coronal hole at the lower-corona level for the first time. At wavelengths longer than 8 cm, we detected circularly polarized emission associated with the passage of an isolated equatorial coronal hole across the disk during two solar rotations (CMP on October 12, 1996, and November 9, 1996). The measured degrees of polarization range from 0.2% ($\lambda = 9$ cm) to 3–4% ($\lambda = 30$ cm). The longitudinal magnetic field is calculated in terms of the thermal bremsstrahlung mechanism for the generation of solar-plasma radio emission in a weak magnetic field. Using Stanford photospheric measurements, we conclude that the longitudinal magnetic field in a coronal hole increases with height from ~0.2 G at the photospheric level to 7–10 G at the level of generation of the 18-cm emission with the subsequent conservation or with a decrease in this strength to the generation region of the 30-cm emission.

INTRODUCTION

Intensive studies of coronal holes (CHs) have been carried out in the last twenty five years. They began after the flight of the Skylab station (1973–1974), during which CHs were detected in the X-ray and extreme UV ranges as "dark" regions in the solar corona. The studies show that CHs are stable, large-scale structures with an open magnetic configuration which differ from the surrounding regions of the quiet Sun by a lower density and temperature and by a temperature gradient in the chromosphere–corona transition region and in the corona itself. CHs are also clearly detected as regions of reduced brightness in the green coronal line and in the microwave radio range and as regions of enhanced brightness with reduced contrast of the chromospheric network in the He I 10830 Å line. CHs are less prominent or entirely invisible in the chromospheric lines (Hα, Ca II) and in the continuum and photospheric lines. At present, the coronal holes are assumed to be reliably identified sources of high-velocity geoeffective solar-wind flows.

Investigation of the physical parameters of the CH atmosphere and magnetic-field structure is important in understanding the nature of these regions and the formation of solar-wind flows. Microwave radio astronomical observations offer a unique opportunity to measure the longitudinal magnetic field in the lower solar corona. In this paper, we present the first magnetic-field measurements in CHs based on RATAN-600 radio observations of the Sun in the 2–30-cm range.

MAGNETIC FIELDS IN CORONAL HOLES

Having compared the positions of CHs detected in the HeI 10830 Å line and in the X-ray and UV ranges during the last two solar-activity cycles with solar magnetograms obtained at ground-based observatories (Kitt Peak, Stanford, Mount Wilson, and others), several authors (Bohlin and Sheeley 1978; Levine 1977; Obridko and Shelting 1989, 1990; Mogilevsky *et al.* 1997) show that at the photosphere, the bases of low-latitude CHs are located in unipolar cells of the large-scale solar magnetic field, in bays and bends of the neutral line while never crossing it. In these cells, the predominant sign of the magnetic field matches the sign of the polar magnetic field of the corresponding hemisphere. The mean longitudinal magnetic field strength at the photosphere beneath CHs varies in the range 0.5–7.5 G, with the most typical values being 2–5 G. At the same time, the mean photospheric magnetic field strength in the CH region is virtually the same as the mean magnetic field strength of the quiet Sun outside CHs.

Calculations of the magnetic fields in CHs at various heights performed in the potential approximation that are based on the fields measured at the photosphere level led to the conclusion that at the source surface (at a distance of 2.5 $R_{\odot}$), CHs are located in hills and bays of the coronal magnetic field. Calculations of the magnetic fields in CHs and numerous observational facts, which suggest the vertical orientation of plasma structures in CHs relative to the solar surface, indicate that an open magnetic-field configuration with radially directed field lines is realized in CHs.

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Magnetographic measurements with a high space resolution reveal a small-scale magnetic-field structure in CHs at the photosphere level with a predominance of one sign of the polarization. For instance, it follows from the observations of Lin (1994) that in the CH studied by him, 90% of the total magnetic flux is provided by the hills of a magnetic field stronger than 100 G that were identified with the boundaries of supergranules and with ephemeral regions. The area of these regions accounted for 10% of the CH area, and the CH magnetic-field strength averaged over the entire area was 7.6 G, which is smaller than that obtained with the same averaging for a quiet-Sun region with mixed polarity outside CHs by a mere 10%.

Evidently, the magnetic-field topology in CHs is an important factor in the formation of high-velocity solar-wind flows. Wang and Sheeley (1990, 1994) pointed to the existence of anticorrelation between the divergence of magnetic field lines in CHs and the solar-wind flow velocity. They noted that the fastest wind flows are generated in the low-latitude parts of CHs, where the magnetic field lines are oriented radially.

Clearly, direct measurements of the magnetic fields in CHs at coronal heights can give decisive evidence for a particular model of the CH structure. At present, the only method of determining the magnetic-field strength (the longitudinal component) in CHs at the upper chromosphere–lower corona level is to measure the circular polarization of CH radio microwave emission. This method is based on the dependence of the thermal bremsstrahlung on the magnitude and direction of the magnetic field (Zheleznyakov 1997); in this case, it is necessary to measure the degree of polarization to within $\leq 1\%$. Currently, the possibilities of directly measuring the magnetic fields in the solar coronal plasma from Zeeman splitting of forbidden coronal infrared lines of several elements, also with a high accuracy of determining the degree of polarization, are discussed (see, e.g., Judge 1998).

Here, we present the RATAN-600 observations of an isolated equatorial CH during the two solar rotations in October–November 1996 (CMP on October 12, 1996 and November 9, 1996) and the measurements of the longitudinal magnetic-field component in the region where the 9–30-cm radio emission is generated, i.e., at the lower-corona level, based on these observations. High-precision RATAN-600 measurements of the circular polarization of solar radio emission have become possible most recently due to the continuous improvements of the receiving and recording equipment and due to the development of software for data reduction (Bogod *et al.* 1997a, 1997b; Garaimov 1997; Garaimov and Bogod 1997).

OBSERVATIONS

The observing period under consideration corresponds to the phase of a deep solar-activity minimum between the 11-year cycles nos. 22 and 23. According to the Solar Geophysical Data (1996), between September 13 and October 20, 1996, no spots or pores were detected on the solar disk, and the monthly mean sunspot number in October 1996 was 0.9, which is a minimum in the last four solar cycles nos. 19–22.

According to the Hα synoptic maps that were kindly provided by V.N. Ishkov (Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Russian Academy of Sciences), a small isolated equatorial coronal hole, surrounded by extended quiet-Sun regions, was detected in the He I 10830 Å line (based on the Kitt Peak data) in October 1996 during the Carrington solar rotation no. 1914. However, no CH was detected in the He I 10830 Å line at this longitude during the next solar rotation. According to the SOHO data, this coronal hole was prominent in the Fe XV 284 Å, Fe XII 195 Å, and Fe IX/X 171 Å lines during the two solar rotations. In the He II 304 Å line (SOHO), the hole was virtually undetectable, but it was pronounced enough in the soft X-ray range on Yohkoh solar images. Note that the more pronounced western boundary of the hole in the X-ray range closely coincided with the CH outline in the ultraviolet lines. At the same time, the CH image in the He I 10830 Å line coincided only with the central part of the X-ray and UV images of the CH [similar facts were noted earlier by Stepanyan (1995)].

During the period under consideration, we carried out regular observations of the Sun with RATAN-600 in the standard mode for solar observations by using the southern antenna sector in combination with a flat periscopic mirror. We recorded daily the intensities of the right- and left-hand circularly polarized components of the solar radio emission simultaneously at 36 wavelengths in the range 1.8 to 29.6 cm during the passage of the Sun through a stationary beam at local noon ($\approx 9^h20^m$ UT). The beam FWHM at 2.0 cm was$17'' \times 13'$. The observations were carried out using a spectral–polarization system—a panoramic spectral analyzer developed by the Solar Radio Emission Group at the Special Astrophysical Observatory under the supervision of V.M. Bogod (Bogod *et al.* 1993, 1997b). During the observations, we used the combined multiwavelength horn feed with a common phase center designed by V.N. Dikii (Bogod *et al.* 1983). For the data reduction, we used the software package developed by V.I. Garaimov (Garaimov 1997; Garaimov and Bogod 1997).

THE RESULTS OF THE RATAN-600 OBSERVATIONS OF CORONAL HOLES

Figure 1 shows some strip scans of full intensity $I = R + L$ of the solar radio emission, obtained on RATAN-600 at several wavelengths in the range 1.8 to 29.6 cm at the time of location of the CH studied in the central part of the disk during two solar rotations. Below the scans, SOHO solar-disk images in the FeXII 195 Å line are given. We see that at wavelengths longer than 4 cm

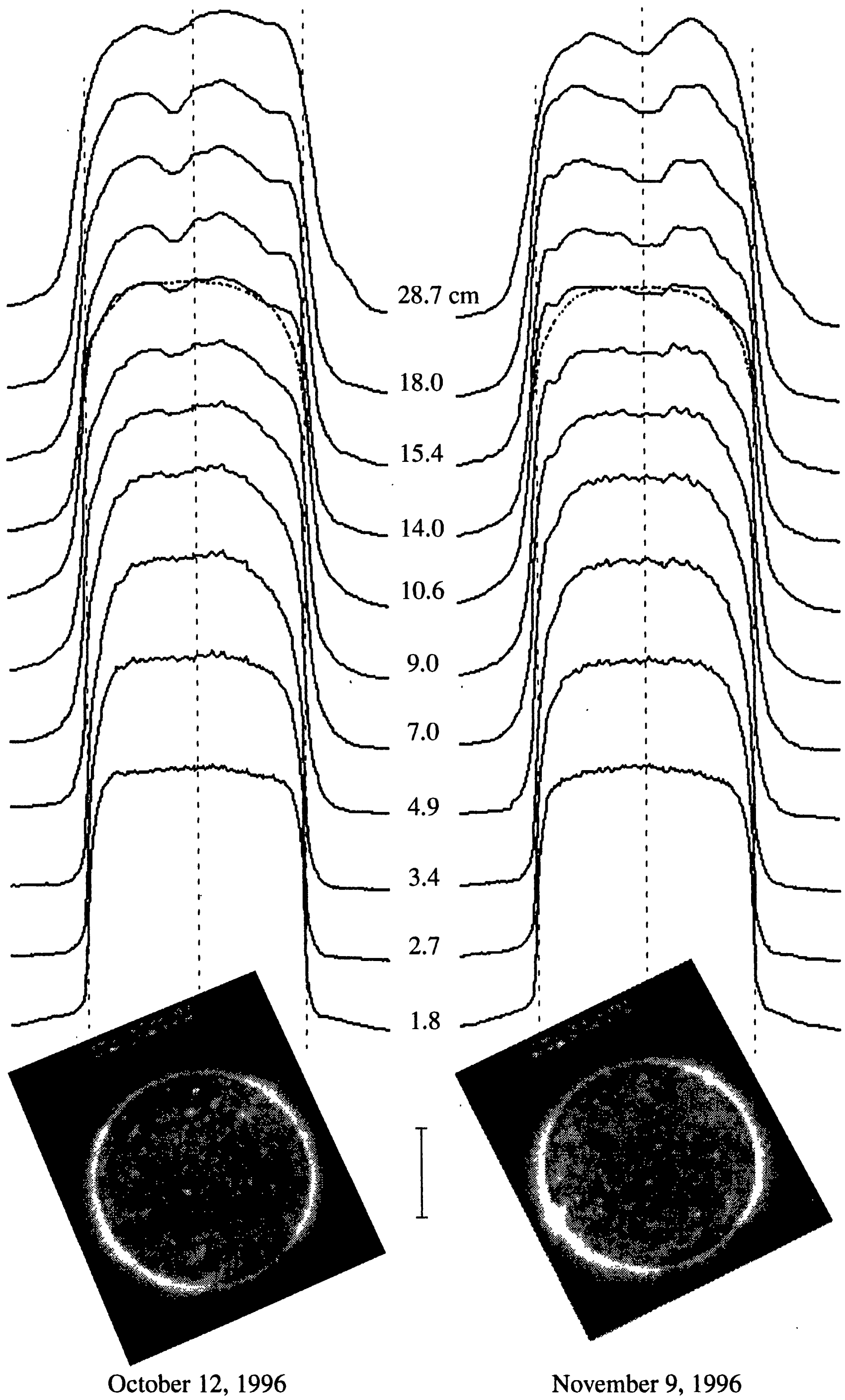

Fig. 1. Sample RATAN-600 records of the solar radio emission in the total-intensity channel (Stokes parameter *I*) at various wavelengths during the central-meridian passage of the CH during two solar rotations. On the 10.6-cm scans, the dashed line shows the level of the "minimum" quiet Sun. Below the scans, solar images in the FeXII 195 Å line for 21^{h}UT are given. The bar in the lower part of the graph corresponds to the RATAN-600 vertical beam width at 2.0 cm.

the coronal hole is visible on the solar scans as a region with lowered radio brightness against the background of the surrounding quiet-Sun regions. As an example, on 10.6-cm scans the profile of the "minimum" quiet Sun is drawn. This profile was obtained as the statistical average from RATAN-600 solar observations during the last two solar-activity minima, we also used daily integral 10.7-cm fluxes of the Sun, measured at the Penticton Station (Solar Geophysical Data 1996). The method of constructing and tracing the quiet-Sun contour on the scans is described in the paper of Borovik (1994).

From Fig. 1, we see that at wavelengths shorter than 4 cm, the CH is not distinguished against the quiet-Sun background; but, at the same time, small-scale sources of enhanced radio emission, which are identified with the brightest X-ray knots, are clearly visible; many of them are also visible in the UV lines. However, a detailed study of radio characteristics of these sources is beyond the scope of this work.

The brightness contrast of the CH investigated against the quiet-Sun background turned out to be somewhat lower than that determined by Borovik *et al.* (1990) for several CHs from similar RATAN-600 solar observations at nine wavelengths in the range 2 to 32 cm during the previous solar-activity minimum between cycles nos. 21 and 22. Typical for this CH was the constancy of the effective horizontal (i.e., along the scan direction) radio size at 5–30 cm, measured when the CH was at the central part of the disk during the two solar rotations (October 12–13 and November 9, 1996); it was 200″ ± 20″ and 325″ ± 15″, respectively. The effective radio size was determined as

$$\varphi_{ef} = (\varphi_{obs}^2 - \theta^2)^{1/2}, \quad (1)$$

where φ_{obs} is the observed size of the CH, i.e., the width of the radio-emission depression at half-maximum depth, and θ is the beam FWHM. In the case considered by us, the largest discrepancies between the effective and observed CH sizes (by factor of more than 2) were at 29.6 cm; they decreased considerably toward shorter wavelengths.

Note that for three CHs of the five studied earlier (in 1984–1987) on RATAN-600, Borovik and Kurbanov (1990) found a growth of CH effective size with a wavelength in the range 8 to 32 cm from 150″–200″ to 250″–350″, respectively; for the two CHs, the radio size at the above wavelength was constant and equal to 310″ ± 10″.

In this study, we have paid main attention to the fact that during the passage of the CH across the solar disk at wavelengths of 9–30 cm, a circularly polarized signal was reliably detected; at shorter wavelengths, it was absent. A sample record of CH-associated polarized 18-cm emission during two solar rotations is shown in Fig. 2. The upper graph shows records of solar radio emission in the channel of intensity I for five consecutive days during the passage of the CH across the solar disk. Arrows indicate the CH-associated depression of the radio emission. The lower graph shows records of the circularly polarized component $V = R - L$ of the solar radio emission. At the record edges, a stable spurious signal in the polarization channel, which is due to displacements of the phase centers of the primary horn feed in the channels of right- (R) and left- (L) hand circular polarization, is visible. At the same time, the right-hand polarized signal (shown with an arrow), which is identified with the CH, is clearly recorded. A dedicated technique investigation showed that cleaning of the records, i.e., minimization of the spurious polarization by means of mathematical processing of the records, has virtually no effect on the magnitude and location on the record of the CH-associated polarized signal.

The degree of polarization P of the radio emission which comes from the CH region was determined as the ratio of the CH antenna temperatures in the channels of circular polarization T^V and intensity T^I:

$$P = T^V/T^I. \quad (2)$$

We took into account (1) the ratio of the vertical size of the CH and neighboring quiet-Sun regions, which are covered by the vertical antenna beam simultaneously with the CH, and (2) the effect of antenna smoothing in the horizontal direction.

The former effect is described by the coefficient $m = D/\eta$, where D is the diameter of the optical solar disk, and η is the CH vertical size, equal to 10′–15′, according to the SOHO CH images in the extreme-ultraviolet lines. We also took into account the fact that at wavelengths of 9–30 cm, the vertical size of the RATAN-600 beam is much larger than the diameter of the optical solar disk. For each observational day, m has a definite, wavelength-independent value.

The latter effect is described by the coefficient $k = \varphi_{obs}/\varphi_{ef}$ which we took into account when we calculated the maximum degree of polarization and constructed its spectrum (see Fig. 4a); we set $k = 1$ when we plotted the distribution of the degree of circular polarization of the CH radio emission along the CH projection onto the diurnal circle (Fig. 3). As noted above, the coefficient k depends strongly on wavelength. It reaches 2–2.5 at 29.6 cm and is close to unity at wavelengths shorter than 15 cm.

Thus, in formula (2) the corrected CH antenna temperatures T^V and T^I are related to their observed values T_{CH}^V, T_{CH}^I and quiet-Sun antenna temperature T_C by the relations

$$T^V = kT_{CH}^V, \quad (3)$$

$$T^I = T_C/m - k(T_C - T_{CH}^I). \quad (4)$$

The distribution of P at 17.1 cm along the scan direction is shown in Fig. 3 (left-hand scales P) for two consecutive days, October 12 and 13, 1996, when the CH was crossing the central meridian. Also shown in this figure are the corresponding segments of solar radio emission records in the channel of total intensity I, on which CH-associated depressions are seen. We see that the maximum degree of polarization is recorded at the hole center and that it decreases to zero at the CH edges.

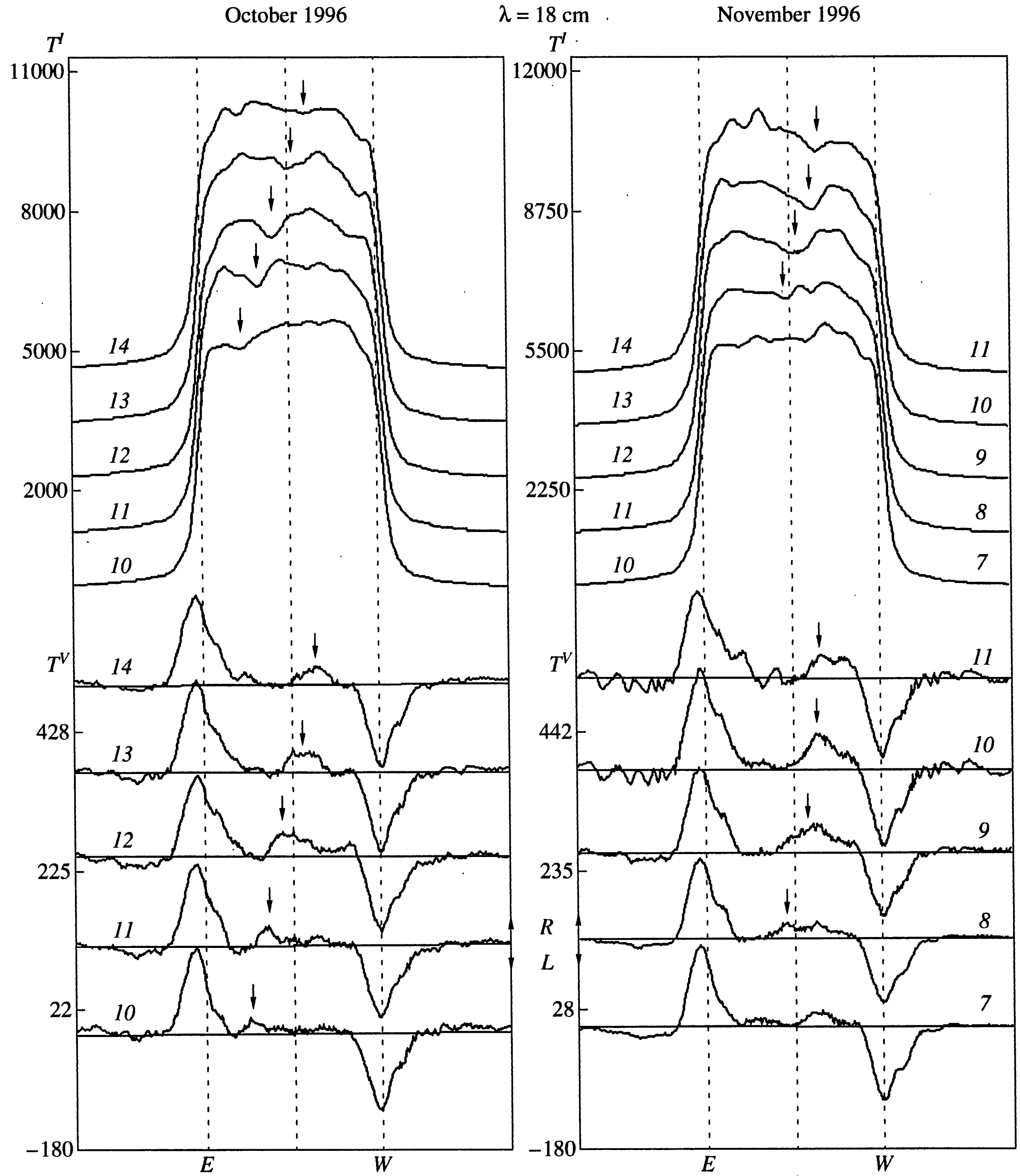

Fig. 2. RATAN-600 solar radio emission records in the channels of total intensity I (upper graph) and circular polarization V (lower graph) at 18 cm, obtained during the days of the central-meridian passages of the CH (October 10–14, 1996, and November 7–11, 1996). The arrows show the region of depressed intensity and the right-hand polarized signal, which are associated with the CH.

The magnetic-field strength (longitudinal component), which is calculated with formula (5) (see below), is shown in the same figure (scale H). The noise component in the distribution of P corresponds to the record of the signal in the channel of circular polarization V and reflects the receiver sensitivity. In Fig. 3 we see that the corresponding fluctuation sensitivity of our observations, with respect to the CH magnetic-field strength, is unrivaled—less than 0.05 G (the value averaged over a solar-surface area of about $2.5' \times 12'$ in size; horizon-

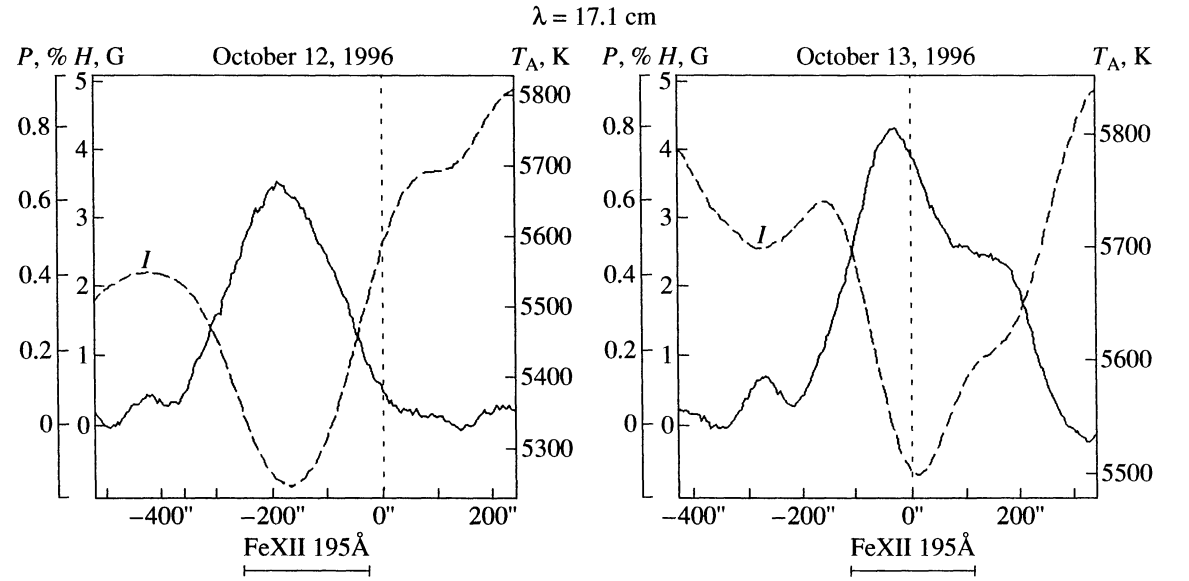

Fig. 3. Hour-angle distribution of the degree of circular polarization P (not corrected for beam smoothing) at 17.1 cm and of the corresponding longitudinal magnetic field H in the CH (solid line). The scales of P and H for each day are given on the left-hand side. The dashed line shows a section of the solar total-intensity I record with the CH-associated depression of the radio emission, the corresponding scales in units of antenna temperature are on the right-hand side. The bar below shows the size of the hour-circle projection of the CH image in the FeXII 195-Å line (SOHO). The dashed line shows the center of the optical solar disk.

tal size—the former figure—is the horizontal beam width, and vertical size—the latter figure—the vertical CH size).

The spectra of maximum degree of polarization P of the CH radio emission in the range 9 to 30 cm are presented in Fig. 4a. The spectra were corrected for the antenna smoothing effect, according to the above-described definition of the effective sizes of the CH. The degree of circular polarization of the CH radio emission is growing with wavelength from 0.2% at 9 cm, reaching 3–4% at 29.6 cm. At shorter wavelengths (1.8–8.0 cm), polarized CH emission was undetectable, the degree of its polarization was less than 0.1%, in accordance with the receiver sensitivity threshold. Vertical bars show the errors of measurement of the degree of polarization at each wavelength, due to the receiver sensitivity and, mainly, due to ambiguity of distinguishing the CH against the quiet-Sun background on the records in the intensity and polarization channels.

DETERMINATION OF THE MAGNETIC FIELD IN CORONAL HOLES

On the basis of the data obtained on the degree of circular polarization of the CH radio emission at various wavelengths of the microwave range, we estimated the CH magnetic-field strength at the generation levels of the radio emission at these wavelengths (in the transition layer and lower corona) under the assumption of thermal bremsstrahlung in a weak, uniform magnetic field. The longitudinal magnetic-field component (in

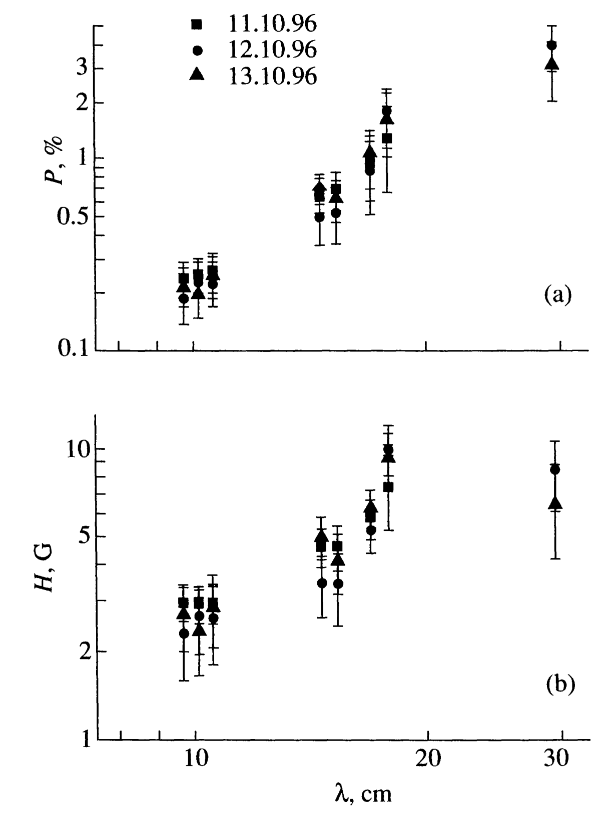

Fig. 4. (a) Spectra of the maximum degree of circular polarization P of the CH radio emission for three consecutive observational days October 11–13, 1996; (b) corresponding longitudinal magnetic fields in the CH, calculated with formula (5).

G) was determined using the formula proposed by Gel'freikh (1972, 1974):

$$H = 107P/\lambda n, \quad (5)$$

where P is the degree of polarization (in per cent), λ is the wavelength (in cm), n is the logarithmic slope of the brightness-temperature spectrum, which was specially determined for the CH from the observations of October 12, 1996, using the method described by Borovik *et al.* (1990). The spectral slope n was 0.9 at wavelengths in the range 9–11 cm, 1.04 in the range 14–18 cm, and 1.7 in the range 27–30 cm. Figure 4b shows the maximum strength of the longitudinal magnetic-field component, calculated with formula (5). It is approximately 2–2.5 G at 9 cm and grows with wavelength to 7–10 G at 18 cm. At longer wavelengths (up to 30 cm) this value either stabilizes or slightly decreases—the accuracy of our measurements does not allow us to draw a definitive conclusion.

DISCUSSION

It is interesting to compare the values of the magnetic field obtained by us with the measurements at the photosphere level. On magnetograms with high spatial resolution (Kitt Peak, Mt. Wilson), published in the Solar Geophysical Data (1996), the region beneath the CH studied by us, at first glance, does not distinguish itself from the neighboring quiet-Sun regions. It is obvious that, for more definite conclusions, it is necessary to process these magnetograms quantitatively, with the purpose of, for example, averaging over an area corresponding to the beamsize of RATAN-600. However, such information can be obtained from low-resolution magnetograms (Stanford, Solar Geophysical Data 1996). The comparison made indicates that the CH studied bu us is projected against a region with positive polarity of the photospheric magnetic field with a longitudinal component strength of about 0.2 G inside a unipolar cell of the large-scale solar magnetic field. This fact is fairly consistent with the works quoted above (Bohlin and Sheeley, 1978; Levine and 1977; Obridko and Shelting 1989, 1990; Mogilevsky *et al.* 1997). Quite a low value of the magnetic field at the photosphere level in this case is probably connected with the time of the deep solar-activity minimum. The north polarity of the CH magnetic field and the right-hand direction of polarization of the radio emission correspond to an excess of the extraordinary-wave emission, in accordance with the theory of thermal bremsstrahlung in a weak magnetic field (Zheleznyakov, 1997). Finally, the photospheric magnetic field measured by us, along with the radioastronomical values we have obtained, leads us to conclude that the magnetic-field strength (longitudinal component) in the CH grows from 0.2 G to 7–10 G in the height interval from the photosphere to the solar corona, where the 18-cm emission is mainly generated, with subsequent stabilization or slight decrease of this value at the heights corresponding to generation of longer-wavelength radio emission (30 cm).

In the papers indicated above, it is noted that the values of the photospheric magnetic field beneath a CH and in the neighboring quiet-Sun regions, as a rule, do not differ markedly. This conclusion is confirmed by the Stanford magnetograms for the timespan of our observations. At the same time, we see from the RATAN-600 observations (Fig. 2) that the polarized signal is definitely identified with the CH and is clearly distinguished against the quiet-Sun background. This may be due to a considerable difference in magnetic-field topology at the level of the upper chromosphere–lower corona in the CH region and above the quiet photosphere. In particular, for the quiet Sun, most magnetic structures are probably closed; thus, in the region of the microwave generation the magnetic field lines have, on the average, horizontal direction. In other words, they have a very small longitudinal component, which accounts for the absence of the polarized signal. In contrast, in a CH, the magnetic structures are open, and the field lines have, on the average, radial direction. This is consistent with the calculations of magnetic-field vectors for different levels above the photosphere, made by Mogilevsky *et al.* (1997) on the basis of synoptic maps of the longitudinal component of the solar magnetic field in the potential approximation.

In our study, we have used observations during the time intervals when the CH was near the solar-disk center, i.e., the angle between the line of sight and the radial direction was sufficiently small, and, consequently, the value of the magnetic-field longitudinal component which we have measured was close to its total value. The observed growth of the magnetic-field longitudinal component with height above the photosphere may be attributed to the fact that the perpendicular component of the magnetic-field structures is decreasing with height, and the radial component becomes dominant because of ordering of the magnetic field lines in the CH.

CONCLUSION

Here, the magnetic-field strength in a coronal hole has been determined for the first time from the RATAN-600 microwave spectral–polarization measurements of the Sun with a high space and frequency resolution. We analyzed the observations of an isolated equatorial coronal hole during the two solar rotations in October–November 1996 (CMP on October 12 and November 9, 1996). High-precision measurements of the circular polarization of the solar radio emission with the RATAN-600 radio telescope have become possible, most recently due to the successive improvements in the receiving and recording equipment, and due to the development of software for data reduction. We reliably recorded the circularly polarized emission which is associated with the passage of the coronal hole across the disk during the two solar rotations. The degree of circular polarization of the radio emission from the coronal hole increases with wavelength from 0.1% at 9 cm to 3–4% at 29.6 cm. The longitudinal magnetic-field component that we determined by using the theory of generation of thermal bremsstrahlung in the presence of a weak magnetic field also increases with wavelength from 2 G at 9 cm to 7–10 G at 18 cm with the subsequent preservation (or possibly with a slight decrease) of this value at 29.6 cm. The mean longitudinal component of the large-scale photospheric magnetic field beneath the hole is ~0.2 G.

The coronal hole studied here had a low contrast in the microwave range and in the other electromagnetic spectral ranges. In general, this hole is not typical, but its remoteness from any active structures and the favorable location relative to the knife-edge antenna beam allowed us to reliably isolate the weak polarized radio signal associated with the hole in a wide wavelength range (8–30 cm) and to estimate the magnetic-field strength in it at the lower-corona level. An examination of the RATAN-600 archival solar observations based on the gained experience shows that weak polarized radio emission is also recorded from other coronal holes, which makes it possible to measure the magnetic fields in them. We plan to perform such measurements later.

ACKNOWLEDGMENTS

In this paper, we used the SOHO data and the archival observations at the observatories of ground-based support for SOHO, the project of international collaboration between the ESA and the NASA. We are grateful to V.N. Ishkov who kindly provided the Hα synoptic maps of the Sun. This study was supported by the Russian Foundation for Basic Research (project codes 96-02-17799 and 96-02-19279), the State Science and Technology Program "Astronomy," and the INTAS RFBR grant 95-0316.

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