THE MAGNETIC FIELD IN THE CORONA ABOVE SUNSPOTS
AT THE ECLIPSE OF 1991 JULY 11

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Received 1992 October 1; accepted 1993 January 26

ABSTRACT

We have used the frequency-agile solar array at the Owens Valley Radio Observatory (OVRO) and the rocket-launched soft X-ray imager NIXT to observe the corona above an active region during the solar eclipse of 1991 July 11. The uncovering of the active region AR 6718 by the Moon allows us to obtain an angular resolution of 1°5 over the frequency range of the OVRO telescope, 1–18 GHz, comparable to the less than 1° resolution of NIXT.

The dominant features of AR 6718 are two leading spots of positive polarity followed by two spots of negative polarity ~3° to the east. Bright ($T_e \approx 2 \times 10^6$ K) radio emission coincides with the positions of the sunspots, attributable to gyroresonance radiation from ambient electrons above the spots. Using a simplified model of the source as a function of distance from the interferometer fringe amplitudes, we obtain brightness temperature spectra for the emission associated with the sunspots. From these data we are able to deduce that the magnetic field strength at the base of the corona above the leading spots was ~1200 G, and ~1100 G above the following spots. The magnetic field spreads and its strength decreases with height in the corona, with the 1200 and 360 G fields covering areas of ~15° and 28° in diameter, respectively. Lower down, in the transition region where $T_e \approx 2$ to 3 \times 10^5 K, the field strength was ~1800 G.

The soft X-ray brightness above the sunspots was very low, ~30 times lower than that of the adjacent plage-association emission. From the X-ray data, supplemented by the electron temperature derived from the radio data, we find that the electron density at the base of the corona above the sunspots was ~1 \times 10^9 cm^{-3}. Combining the X-ray and radio data, we derive an upper limit to the gradient of field strength with height: $|\nabla B| \lesssim 1.5 \times 10^{-8}$ G cm^{-1}.

Subject headings: eclipses — Sun: corona — Sun: magnetic fields — sunspots

1. INTRODUCTION

The magnetic field in the solar corona is poorly known because there are few observations of that can measure it unambiguously. It has not been measured with confidence from Zeeman splitting of coronal lines. Extrapolations from the photospheric magnetic field are valuable in some circumstances, but they do not take into account electric currents in the corona and their associated fields. The field in active regions predominates and it has been inferred from several direct and indirect methods such as requirements for stability, thermal insulation, forms of loops, oscillations, and the Hanle effect. These measurements indicate that few or no prominences have field strengths above 150 G, and typical strengths are 26 G (Harvey 1969). These observations apply to the field within active regions, but not the field above sunspots. During flares, microwave radio observations have been used by many authors to estimate the magnetic field in the regions containing the high-energy electrons. Typical values obtained apply to a higher region of the corona than is relevant here, often away from sunspots.

The most reliable information on the magnetic field in the corona above sunspots probably comes from microwave observations between ~3 and 15 GHz. In this frequency range, bright emission is often observed, emission that is localized above and near sunspots; it is reliably attributed to gyroresonance radiation at the second and third harmonics of the gyro-frequency (e.g., Kakinuma & Swarup 1962; Zheleznyakov 1962; Takakura 1972; Ramaty & Petschan 1972; Lee, Gary, & Hurford 1993a). High-resolution observations by the Westerbork and Stanford interferometers, with the RATAN 600, and with the VLA, mostly near 5 GHz, have confirmed the role of gyroresonance emission by showing vividly that radiation of high brightness temperature, $T_B \gtrsim 10^6$ K, and high degree of circular polarization (up to 100%) is localized above sunspots (e.g., Alissandrakis, Kundu, & Lantos 1980; Krüger et al. 1986; Alissandrakis, Kundu, & Shevgoor 1991), or found in a sort of ring structure near them (Shibasakii et al. 1979; Shibasakii et al. 1983; Alissandrakis & Kundu 1982; Lang & Wilson 1982).

At frequencies lower than ~3 GHz the same localization of emission is not observed. Instead, radiation of $T_B \gtrsim 10^6$ K covers most or all of the active region. This radiation is of low polarization (~20%), and has been convincingly attributed to free-free emission from the hot, dense electrons that are confined in the strong magnetic field (Chiuderi-Drago, Felli, & Tofani 1977; Dulk & Gary 1983; Lang & Wilson 1983). This is not to say that gyroresonance radiation does not occur at these

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The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.
frequencies; rather, it lies at relatively low altitudes in the corona and is covered over most or all of the active region by optically thick, free-free radiation.

Similarly, at frequencies higher than ~15 GHz, the bright emission has largely disappeared (e.g., Chiuderi-Drago et al. 1982; Lang, Wilson, & Gaizauskas 1983), although at 15 GHz it is reported occasionally (White et al. 1991; Lim, White, & Kundu 1992). For these high frequencies, the high magnetic field strengths required for gyroemission at the second or third harmonics (B ≥ 2000 G) rarely exist in the corona, and the gyroresonance opacity at the fourth and higher harmonics is ≲1. Furthermore, because the opacity of free-free emission from the active regions decreases continually with frequency and is less than unity starting at ~2 or 3 GHz, active regions observed at short-centimeter, millimeter, and submillimeter wavelengths contain features of lower and lower contrast (e.g., Hurford 1986; Lindsey et al. 1990; Ewell et al. 1993).

Observations of active regions at a large number of frequencies are relatively rare. Early Ratan 600 (Akmdov et al. 1982, 1983; Krüger et al. 1986) and OVRO observations (Hurford, Gary, & Garrett 1985) have been used to deduce information on magnetic fields in the corona above sunspots. The most definitive study so far of gyroresonance radiation above sunspots is probably that of Gary & Hurford (1987) who observed a partial eclipse at 1.4 and 4.9 GHz with the VLA and nearly simultaneously at 16 frequencies between 1.4 and 8 GHz with the frequency-agile interferometer at the Owens Valley Radio Observatory (OVRO) (Hurford, Read, & Zirin 1984). The combination of spatial and spectral resolution allowed them to observe the change in emission mechanism from predominantly free-free to gyroresonance at ~3 GHz. In addition they demonstrated that gyroresonance emission over one sunspot terminated in the x-mode (harmonic s = 3) at ~5 GHz, so the maximum magnetic field in the low corona was ~600 G. For the other sunspot, gyroresonance emission continued in both o- and x-modes to the highest observed frequency of 8 GHz. Thus the second harmonic (s = 2) of the gyromagnetic band in the low corona was at least 8 GHz and the field strength was at least 1400 G.

Three antennas at OVRO were used by Lee, Hurford, & Gary (1993b) and Lee et al. (1993a) to follow an isolated sunspot from center to limb. From these data they were able to derive the strength of the magnetic field in the corona as a function of distance from sunspot center, finding it to have a Gaussian form with half-width at 1/e of 11' and maximum strength of 1400 G. In addition, they were able to verify directly from their observations that the dominant harmonic numbers were s = 2 for the o-mode and s = 3 for the x-mode, and they were able to account for the change of polarization and disappearance of ringlike features in the brightness distribution as the sunspot approached the solar limb.

In this paper we utilize observations made at OVRO during the eclipse of 1991 July 11, supplemented by soft X-ray observations made at nearly the same time by the Smithsonian Astrophysical Observatory NIXT experiment on a NASA sounding rocket, and by Hα and magnetogram observations from the Big Bear Solar Observatory. From OVRO, data are available at 14 frequencies between 1 and 18 GHz and from three antennas. We concentrate on the data obtained when the Moon was uncovering an old active region where the leading and following sunspot groups were well separated, with each group containing two dominant sunspots. We are able to determine the spectrum and polarization of the gyroresonance radiation, measure the maximum frequency in the o- and x-modes, from which we derive the highest magnetic field strength in the corona, and measure the spreading of the magnetic field with decreasing frequency, i.e., as a function of height above the sunspot and/or with distance from the spot centers.

In §2 we present the OVRO observations, the derived spectra, and the NIXT observations, in §3 we present our model of the magnetic field in the corona, and its gradient derived by combining the radio, soft X-ray, Hα, and magnetogram data, and in §4 we summarize and present our conclusions.

2. OBSERVATIONS AND METHOD OF ANALYSIS

2.1. The Active Region

The eclipse of 1991 July 11 was partial as observed from OVRO, with a maximum of ~80% of the Sun being covered. Figure 1 shows an Hα photograph taken at Big Bear Solar Observatory (BBSO) near the beginning of the eclipse. The area of interest in this paper is AR 6718, located at latitude S25° and longitude E10°-E25°. Active region AR 6718 is an old one, with two leading spots of positive polarity followed by two spots of negative polarity ~3' to the east. The circle on Figure 1 shows the location and size of the primary beam of the two 27 m antennas at 10 GHz at the time of the observations, i.e., when this active region was being uncovered by the Moon.

Figure 2a shows the BBSO magnetogram taken ~4 hours earlier. The relative simplicity of the active region field is clear. Figure 2b shows the structure of the corona of AR 6718 as recorded in soft X-rays by the Normal Incidence X-ray Telescope (NIXT), which was launched on a rocket from White Sands ~2 hours before our observations. This instrument observes the entire disk of the Sun with a resolution of less than 1', it is described in detail by Spiller et al. (1991). Briefly, the multilayer mirror has a passband of 1.4 Å at 63.5 Å, the wavelength of emission lines of Mg x and Fe xvi that are formed at temperatures T ~ 10⁶ K and 3 × 10⁶ K, respectively. On Figure 2b the locations of the principal sunspots are outlined by white contours taken from the magnetogram of Figure 2a; the two images are shown with the same scale. We note that hardly any coronal material is visible above the sunspots, nor are any coronal loops visible that directly connect the leading and following sunspot groups. Instead, there is a well-developed arcade of coronal loops that appears to emanate from the leading polarity field in the plage between the sunspot groups and to terminate in the plage to the southeast of the following group.

Figure 3 is a high-resolution photograph of the active region as recorded in Hα at BBSO after the eclipse, ~1 hour after our observations. The details of the two sunspot groups are evident, with two principal spots in each of the leading and trailing groups, but with the last one being composed of several closely packed spots. The active region filament that parallels the neutral line is clearly evident, as are the two plage regions which are the footpoints of the coronal loops of the NIXT photograph.

2.2. Radio Observations

2.2.1. Overview

The three antennas at OVRO that observed the eclipse were arranged in a triangle, with antenna A (27 m) being located at
61 m north of array center, antenna B (27 m) at 488 m east of array center, and antenna C (2 m) at 366 m north of array center. The interferometer fringes of the BC pair were parallel to the edge of the Moon (within 2°) as it uncovered the active region AR 6718 described here.

About 10 minutes before the Moon uncovered AR 6718, the antennas were pointed to the center of the active region (see Fig. 1) and began tracking it. Observations were continuously made during the occultation at 18 frequencies between 1 and 18 GHz, but four frequencies are not used in this study because of contamination by interference or confusion. The total power observed by the three antennas was recorded at 5 s intervals, along with the amplitude and phase of the correlated signal in the three interferometer baselines. Both right-hand and left-hand circular polarization were recorded on the AB baseline, while linear polarization was recorded on the BC and CA baselines (as linearly polarized radio emission from the Sun is not detectable at Earth, these baselines are equally sensitive to right-hand, left-hand and unpolarized radiation).

The complex fringe visibilities from the three baselines were vector differentiated in time so that each differenced sample represents the amplitude and phase due to sources within a narrow window defined by successive positions of the solar limb. For 5 s samples, with the Moon's limb moving at 0°.362 s⁻¹, this corresponds to an angular resolution of 1.81 in the direction of motion of the Moon's limb. The time profile at any of our measured frequencies thus corresponds to a one-dimensional profile of the flux or brightness temperature across the active region. For the BC baseline, with its fringes parallel to the Moon's limb, the flux profile and fringe amplitude profile are nominally identical, while for the other baselines the fringe amplitude and phase contain some information on the structure of the active region in the perpendicular direction, along the lunar limb.

The trace that is overlaid on Figure 3 shows the profile of fringe amplitude from baseline AB at 8.2 GHz as the active region was uncovered. At 8.2 GHz, as at all frequencies higher than ~4 GHz, the high amplitudes are associated only with the sunspots; very little flux is associated with the plages. The radio flux is more extensive than the sunspot umbrae and slightly more extensive than their penumbrae. The highest amplitude tends to occur near the outside edges of the sunspots. A decrease in amplitude is evident near the dividing line between the two spots of each pair. As described below, we attribute this decrease not to a real decrease in brightness temperature, but rather to destructive interference on the AB baseline as the source shifts from one sunspot of the pair to the other.

2.2.2. Radio Spectra

Figure 4 shows the dynamic flux spectra from ~2.5 to 18 GHz during the time that the Moon uncovered AR 6718, as measured on two of the three baselines. The baseline BC, composed of one 5 m and one 27 m antenna, was oriented so that its fringes were essentially parallel to the Moon's limb. Hence the measured BC fringe visibility profile can be interpreted as a flux density profile. The baseline AB, composed of two 27 m antennas, was oriented so that the fringes were tilted by 24° to
the Moon’s limb. Thus, as explained in detail later, the AB fringe visibility profile differs from the flux density profile.

The first high-intensity portion of the flux density profile occurred during deoccultation of the leading (west) sunspot pair, and the second occurred during deoccultation of the following pair. Comparing the flux density observed in the BC baseline (top panel) with the fringe visibility amplitude of the AB baseline (middle panel), there are several similarities and differences. The similarities are (1) The envelope of the intense emissions is the same, being wider at the lower frequencies. (2) The start and end times of the intense emissions are nearly identical. (3) The noise level increases with time on both baselines, but particularly BC; this is because the radiation from a larger and larger part of the Sun’s disk enters the antennas during the deoccultation. The differences include: (1) The gaps are present in emission on AB that divide the two spots of each pair; these will be discussed below. (2) Radiation extends to somewhat higher frequencies on the AB profile than on BC; this is because the AB baseline, with two 27 m antennas, is more sensitive (particularly at high frequencies) than the BC baseline with one 27 m and one 2 m antenna. (3) Radiation of moderate intensity seems to be present on the BC baseline from ~6–9 GHz in the plage region between the two sunspot pairs, but does not appear in the AB baseline data. We believe that this emission on BC is real, and not noise, because the phases continue to advance in step with the Moon’s position. We have no detailed explanation for the form of this spectrum; however, it is not essential to the main purpose of this paper, which is to examine the radiation above the sunspots. A likely explanation for why the emission does not appear on the AB baseline, whose fringes are not parallel to the Moon’s limb, is that the plage source extends so far along the limb that it is resolved out. We calculate that an extent of the plage source along the lunar limb of ≥32° can account for the observations.

The bottom panel of Figure 4 shows the degree of circular polarization as measured on the AB baseline. The degree of polarization is high (≥0.4) only at the edges of the sunspots and at the highest frequencies. In these locations the leading sunspot pair exhibits right-hand polarization and the following sunspot pair exhibits left-hand polarization. These senses of polarization, in conjunction with the polarity of the sunspot field shown in the magnetogram of Figure 2a, demonstrate that
the radiation is in the x-mode. At the lower frequencies, well inside the gyroresonance emission regions, the degree of circular polarization is low, and in some places it is of the opposite sense from that at the higher frequencies.

The most important point to note in both panels of Figure 4 is the widening of the sunspot-associated emission regions with decreasing frequency. For example, the duration of the emission at 10 GHz is \( \sim 80 \) s while that at 4.2 GHz is \( \sim 140 \) s. Because the lower frequency radiation originates at lower field strengths higher in the corona and/or farther from the spot, this widening demonstrates vividly the gradient of the sunspot coronal field.

2.2.3. Geometry of Deoccultation

Figure 5a shows the relationships among the photospheric sunspots (as traced from an off-band Hα photogaph from BBSO), the Moon’s limb, and the interferometer fringes at the time when the first spot of the western pair was being uncovered. With the Moon’s center moving at a rate of \( 0.396 \) s\(^{-1}\) in the direction \( 18^\circ \) S of E and the angle between this motion and the Moon’s limb being \( 66^\circ \), the rate of uncovering of a spot is \( 0.396 \) s\(^{-1}\) \( \times \sin 66^\circ = 0.362 \) s\(^{-1}\).

Figure 5b shows the detail of the deoccultation of the first pair, with the Moon’s limb about half-way between the two sunspots. The slit uncovered by the Moon in a \( 5 \) s interval is \( 1.81 \) wide, and it intersects portion “a” of the western spot and portion “b” of the eastern spot. The BC baseline, with its fringes essentially parallel to the Moon’s limb, contains no information on the structure parallel to the limb, but gives unambiguous information perpendicular to it. The AB baseline has its fringes tilted at an angle of \( 42^\circ - 18^\circ = 24^\circ \) to the limb (see Fig. 5a) and from the differences between the BC and AB profiles we can derive information on source structure along the limb. The fringe spacing of the AB baseline is \( 128''/f_b \) where \( f_b \) is the frequency in GHz, so the distance between a “positive” fringe and a “negative” fringe is \( 6.4 '' \) at 10 GHz. The solid and dashed lines on Figure 5b are separated by 6.4 We note that this separation approximately matches the distance between the parts a and b of the two spots.

In the circumstances just described, if the intensities of a and b are about equal, then there is destructive interference on the AB baseline and the fringe amplitude approaches zero. Furthermore, as time progresses and the “slit” (the region uncovered by the Moon in \( 5 \) s) moves from the first spot to the second, the phase of the complex visibility should change abruptly by 180°. This is just what is observed in the range of frequencies of \( \sim 7-12 \) GHz. Figure 6a shows the time progression of the AB fringe amplitude and phase at 8.2 GHz. There is a regular phase winding in the “raw” phases plotted in the middle panel of Figure 6a as the Moon uncovers each spot that is due to the motion of the Moon across the field of view. Superposed on this regular winding is a sudden jump of \( \sim 180^\circ \) that coincides with the minimum in fringe amplitude, i.e., when the phase center shifts from the western to the eastern spot of the pair. This is more easily seen in the lower panel of Figure 6a, where the regular phase winding has been removed from the phases.

Figure 6b shows the same thing except at 4.2 GHz. There is no sudden jump in the phase, but rather a smooth phase shift, because the spacing between positive and negative fringes at 4.2 GHz is \( \sim 15^\circ \), which is larger than the separation between “a” and “b” in the direction perpendicular to the fringes. The
Fig. 4.—Dynamic spectra of fringe amplitude as the Moon uncovered the active region. *Top panel*: Linearly polarized radiation from the BC baseline (fringes parallel to the Moon's limb). The contours are 0.015, 0.02, 0.03, ..., 0.11 SFU. *Second panel*: Total intensity from the AB baseline (fringes tilted by 24° from the Moon's limb). The contours are 0.02, 0.04, ..., 0.12 SFU. *Third panel*: Degree of circular polarization $V/I$ of the LH polarized radiation, with white representing $V/I < 0.2$, black representing $V/I > 0.75$, and the other two contours being at $V/I = 0.4$ and 0.6, respectively. *Bottom panel*: The same except for RH polarized radiation. The apparent decrease in flux below ~2.4 GHz is artificial; lower frequencies were dominated by interference noise and have been removed from the plots.

Fig. 5.—(a) Geometry of the active region, showing the interferometer fringe angles, the orientation of the Moon's limb and the motion of the Moon's center at the time the first spot of the leading pair was being uncovered. (b) Detailed trace of the two sunspots of the first pair showing the strip uncovered by the Moon in 5 s and the orientation and spacing of the interferometer fringes of the AB baseline at 10 GHz.
decrease in 4.2 GHz fringe amplitude at the time of the 8.2 GHz phase jump is consistent with a partial interference between the two components.

2.2.4. Radio Source Sizes

In order to account for the main features of the radio spectra of Figure 4 and the way that they are associated with the visible sunspots of Figure 3, we model the emission regions above each sunspot pair as two Gaussians of the same size. Specifically we assume that the brightness temperature distribution above each spot is given by

$$T_b(f) = T_{b0}(f) \exp \left\{ -\left( \frac{x - x_0}{w_s(f)} \right)^2 \right\},$$

where $T_{b0}$ is the brightness temperature at spot center, $x - x_0$ is the distance from spot center, and $w_s(f)$ is the half width at $1/e = 0.368$ intensity. Noting that the minimum of AB fringe amplitude is almost centered between the two spots of each pair, we find it convenient to measure the full width of the two spots at $1/e$ intensity and take this to be $4w_s$. In this process we used a series of fixed-frequency plots similar to Figure 6, measuring the $1/e$ width of the fringe amplitude from the AB baseline where the signal to noise ratio is the highest. We find that the radio source size above the spots of the leading pair is slightly ($\sim 10\%$) larger than that above the following pair, and that they are well described by the empirical relation:

$$w_s(f_0) = 19'6 - 12'2 \log (f_0),$$

where $f_0$ is the frequency in GHz and the limits of validity are $3 \leq f_0 \leq 14$ GHz. To derive this relation we converted from time to distance using the fact that the Moon uncovered circular regions at a rate of $0'362 \text{ s}^{-1}$.

We believe that this relation describes the radio source size at all frequencies between $3$ and $14$ GHz (see Fig. 4). At these extremes we have $w_s \approx 13'8$ (3 GHz), and $w_s \approx 5'6$ (14 GHz).

2.2.5. Sample Brightness Temperature

The observed flux densities $S(f)$ can be converted to brightness temperatures using the source sizes derived above in the relation

$$T_b(f) = \frac{S(f) \lambda^2}{k \Omega} \approx 2.77 \times 10^{10} \frac{S_{\text{SFU}}}{f_0^2 A},$$

where $k$ is Boltzmann’s constant, $\Omega$ is the solid angle subtended by the source, $S_{\text{SFU}}$ is the flux density in one polarization in units of $10^{-22}$ W m$^{-2}$ Hz$^{-1}$, and $A$ is the area of the emitting region in arcsec$^2$. The flux density measured with the antennas must be corrected for the primary beam, whose size at 10 GHz for a 27 m antenna is shown on Figure 1. The primary beam is different for the two baselines, but can be considered as a Gaussian with FWHM $h$, i.e.,

$$B(r,f) = \exp [-4 \ln 2 \times (r/h)^2],$$

where $r$ is the distance of the source in arcminutes from the pointing center. For the AB baseline, using two 27 m antennas,
$h = 46.5/f_o$, while for the BC baseline, with one 27 m antenna and one 2 m antenna, the FWHM is larger, $h = 65.6/f_o$.

For spot center, the area of the source will be $A = 2w_x w_y$ where $w_x$ is the source size parallel to the Moon’s limb as defined above and $w_y = 1.81$ is the width of the region uncovered by the Moon in the 5 s sample time. As an example, we compute the maximum brightness temperature over the first pair of sunspots, first at 8.2 GHz and then at 4.2 GHz. At 8.2 GHz on baseline BC we observed $S \approx 0.107$ SFU and $w_y \approx 8.5$. The primary beam correction near sunspot center is 1.19, so after correction the true flux density is $S \approx 0.127$ SFU. At this same location, the area of the source is $A \approx 31$ arcsec$^2$ and hence $T_B \approx 1.7 \times 10^6$ K. At 4.2 GHz, the measured $S \approx 0.059$ SFU, the beam correction is smaller, 1.05, and $w_y \approx 12.0$, so that $T_B \approx 2.2 \times 10^6$ K.

Performing the same calculation for the amplitudes measured on the AB baseline, we obtain approximately the same result as on the BC baseline at 4.2 GHz, but a result about half as large at 8.2 GHz. We attribute the difference at 8.2 GHz to the partial resolution of the source by the AB interferometer pair.

2.2.6. Spectra of Brightness Temperature

We can apply the above method to each of the frequencies measured on the BC baseline at points over the sunspots where the model of source size is valid. This yields brightness temperature spectra that can be used to evaluate the correctness of our model of source size as a function of frequency, and if the model is shown to be consistent at all frequencies, to give the electron temperature and magnetic field strength at the base of the corona above the spots.

A correct model should produce a gyroresonance spectrum characterized by a constant brightness temperature at low frequencies where the coronal emission is optically thick, and an abrupt decrease in brightness temperature at higher frequencies where the coronal emission has become optically thin, i.e., at frequencies where the field strength in the corona is inadequate to produce gyroradiation at the second or third harmonic. Figure 7a shows the brightness temperature spectrum over the leading (western) pair of sunspots at three locations: over the center of the spot pair, 9° west of the center, and 18° west of the center. The spot center spectrum (filled squares in Fig. 7a) shows a gyroresonance character just as we expect. The rapid fall-off of $T_B$ at $\sim 10$ GHz can be used to determine the magnetic field strength at the base of the corona once it is known which harmonic of the gyrofrequency is responsible, as has been shown, for example, by Lee et al. 1993a.

2.2.7. Magnetic Field Strength at the Base of the Corona

From the spot-center spectrum for the leading spots (Fig. 7a), we determine that the central magnetic field strength of the leading spot pair at the coronal level is $\sim 1200$ G, assuming that the highest optically thick harmonic is $s = 3$. This value pertains to the base of the corona where the electron temperature is $\sim 2 \times 10^6$ K. The coronal magnetic field above the trailing pair of spots is marginally smaller, at $\sim 1100$ G. We regard the spectra shown in Figure 7 as confirmation of our model source geometry, since it fits the amplitude, phase, and polarization data on both baselines AB and BC, and agrees with theoretical expectations of spectral shape and absolute brightness temperature.

Off the spot center (plus symbols in Fig. 7a), the brightness temperature drops from $2 \times 10^6$ K to $\sim 10^5$ K at $\sim 6$ GHz, but does not drop precipitously until near 9 GHz—about the same frequency as the spot-center spectrum. Farther from the spot center, the third spectrum (open squares in Fig. 7a) shows a rapid decrease near 5 GHz.

For completeness, in Figure 7b we plot the brightness temperature spectrum from the trailing (eastern) pair of spots, both at the center of the spots and again at 9° east of center. The spectra resemble those of the western spot pair.

There are intriguing features in the spectra that may be due to a transition from optically thick emission in both modes (the spot-center spectrum of Fig. 7a) to optically thick in only one mode (the spectrum 9° from spot center). But because of the limited precision of the data, and because our $T_B$ spectra are obtained from a simple model (i.e., circularly symmetric Gaussians), a detailed model of the magnetic field sufficient to explain the spectra cannot be generated from the present observations.

In addition to the gyroresonance character of the spectra in Figure 7, we tentatively identify the high-frequency tail of emission in the spectrum in Figure 7b, farthest from the center of the trailing spots, as optically thin thermal bremsstrahlung, since it shows an approximate $f^{-2}$ dependence. We will discuss this further in the next section.

2.3. X-Ray Brightness and Electron Density above the Sunspots

We remarked in § 1 that the soft X-ray brightness as recorded by NIXT was very weak above the sunspots of AR 6718.

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**Fig. 7.—Spectra of brightness temperature. (a) At 3 times during the uncovering of the first sunspot of the western pair. (b) Same, but during uncovering of the eastern pair.**
Above the sunspots the intensity was about a factor of 30 lower than above some parts of the loops and plage (see Fig. 2b). This phenomenon of low X-ray intensity above sunspots has previously been noted, for example, by Pallavicini et al. (1979), and Webb & Zirin (1981).

We have used the measured X-ray flux at the position of the umbra of the leading sunspot to estimate the columnar electron emission measure \( \int n_e^2 dl \) and electron density \( n_e \) at the base of the corona above the spot. The absolute calibration of the NIXT instrument was obtained at the NSLS synchrotron facility and also by several different types of laboratory calibrations (Spiller et al. 1991), and is estimated to be good to \( \pm 5\% \). Hence the emission measure should have a similar accuracy and the electron density (taking a square root) should be good to \( \pm 30\% \).

The derived values of emission measure and electron density vary somewhat, depending on coronal temperature, because the intensities of the Mg xxv and Fe xxvi lines in the NIXT passband vary with temperature. In addition, in order to convert emission measure to electron density at the base of the corona it is necessary to know the electron distribution with height, which we assume to be exponential with a scale height given by the coronal temperature. This assumption is justified for the low corona above the umbrae of sunspots, where the magnetic field is nearly vertical.

Table 1 gives the values of \( \int n_e^2 dl \) and \( n_e \), for assumed coronal temperatures between 1 and \( 3 \times 10^6 \) K. Table 1 shows that the electron density at the base of the corona derived in this way changes by only a factor of \( \sim 2 \) over this temperature range. Furthermore, the radio brightness temperature shows that the actual electron temperature was \( \sim 2 \times 10^6 \) K. Hence we conclude that the electron density in the low corona above the spot umbrae was \( \sim 10^6 \text{ cm}^{-3} \).

As we mentioned in the previous section, the high-frequency tail on our \( T_B \) spectrum at the edge of the trailing spot pair in Figure 7b resembles an optically thin bremsstrahlang (free-free) spectrum, probably due to higher density plage sources within the slit defined by the Moon’s motion in 5 s. The actual \( T_B \) indicated by this tail is not necessarily correct, however, because the \( T_B \) was determined using a source size valid only for the spots and not for the plage areas. It is likely that the plage source extends a longer distance along the Moon’s limb than our model for the spots assumes, so that the \( T_B \) in the high-frequency tail of Figure 7b is overestimated. The free-free spectra can be used, however, to get an upper limit to the column density of coronal electrons. Extrapolating the \( f^{-2} \) dependence in the high-frequency tail back to lower frequencies allows us to estimate that \( \tau = 1 \) occurs at \( \sim 4.5 \text{ GHz} \) (see the spectrum of Fig. 7b). We use the expression for free-free optical depth in a \( 2 \times 10^6 \) K corona (e.g., Dulk 1985),

\[
\tau = \phi f^{-2} \int n_e^2 T_e^{-3/2} dl.
\]

Putting \( f = 4.5 \text{ GHz}, T_e = 2 \times 10^6 \) K and \( \tau = 1 \), we find that \( \int n_e^2 dl \), the column density of coronal electrons (averaged over slit), is

\[
\int n_e^2 dl \approx 2.6 \times 10^{29} \text{ cm}^{-5}.
\]

This value is about a factor of 30 larger than the corresponding value \( 9 \times 10^{27} \text{ cm}^{-5} \) for the umbrae of sunspots in Table 1, and somewhat fortuitously corresponds exactly to the difference in X-ray brightness above the sunspots to the plage outside. Noting that the X-ray brightness is proportional to \( \int n_e^2 dl \), this is consistent with the idea that the high-frequency tail is due to free-free emission, although its shape and the value of brightness temperature cannot be interpreted directly.

3. Interpretation

3.1. Magnetic Field Strength above Sunspots

As discussed in § 1, it is well established that gyroresonance emission occurs at harmonic \( s = 2 \) in the \( \alpha \)-mode and at harmonic \( s = 3 \) in the \( \chi \)-mode. From Figure 7 we see that the brightness temperature falls below \( 10^6 \) K at \( \sim 10 \text{ GHz} \). From Figure 4 we see that the sense of polarization indicates that the radiation is in the \( \chi \)-mode. Thus we conclude that the maximum gyrofrequency at the base of the corona was \( 10^3 / 3 = 3.3 \text{ GHz} \), corresponding to a magnetic field strength of 1200 G.

At 3 GHz, the lowest frequency at which gyroresonance radiation stands out clearly from free-free radiation, the low polarization near sunspot centers indicates that the radiation is in both the \( \chi \)- and \( \alpha \)-modes. Thus at the highest observable coronal level (the \( \chi \)-mode at \( s = 3 \) for the lowest observable frequency), the gyrofrequency was 1.0 GHz, corresponding to a magnetic field strength of 360 G.

For the portions away from sunspot centers, toward the edges, the polarization at all frequencies shows that the radiation was in the \( \chi \)-mode, indicating radiation at harmonic \( s = 3 \), and hence field strengths lower than the maximum values quoted above. For example, from Figure 7a at 18° west of the spot center, the highest field strength has dropped to \( \sim 600 \) G.

While the value 1200 G derived above is the maximum field strength at the base of the corona, we note on Figure 4b that emission is observable up to \( \sim 15 \text{ GHz} \). The brightness temperature, however, decreases above \( 10 \text{ GHz} \) and is only 2 to \( 3 \times 10^5 \) K at 15 GHz. This emission (Fig. 4b) is visible only above the sunspots, it does not occur elsewhere in the active region, it is clearly a continuation of the coronal gyroresonance emission, and it is in the \( \chi \)-mode. Therefore we attribute it to gyroresonance radiation in the transition region where the temperature is a few times \( 10^5 \) K.

We have considered whether this high frequency radiation is at the third or the fourth harmonic of the gyrofrequency. We find that emission at the fourth harmonic is optically thin and does not contribute much brightness, and conclude that this 15 GHz radiation is optically thick gyroresonance emission at \( s = 3 \) from the transition region where the temperature is \( 2-3 \times 10^5 \) K and the magnetic field strength is \( \sim 1800 \) G.

3.2. Magnetic Field Decrease with Height

We know of no direct way of establishing the height at which our derived values of field strength apply. However, by the following procedure we obtain a lower bound on \( L_B \), the distance scale over which the magnetic field decreases:
The optical thickness $\tau$ of gyroresonance radiation is given by (e.g., Dulk 1985):

$$\tau = \kappa L_B = \left( \frac{\pi}{2} \right)^{5/2} \frac{2 f}{c f s} \frac{s^2}{s^2} \left( \frac{\beta^2}{\sigma} \sin^2 \theta \right)^{-1} \left( 1 - \frac{\cos \theta}{\theta} \right) L_B,$$

where $\kappa$ is the linear absorption coefficient, $f$ is the plasma frequency, $\beta^2 = k T_e/m_e c^2$, and $\sigma = +1$ for the $o$-mode and $\sigma = -1$ for the $x$-mode.

In that equation, $L_B = B/V_B$ is the quantity we wish to estimate. To do this we put $n_e = 10^9$ cm$^{-3}$ ($n_e = 2.8 \times 10^6$ Hz), $T_e = 2 \times 10^8$ K so that $\beta^2 = 3.3 \times 10^{-4}$, and $\theta = 30^\circ$ which is appropriate for the vertical field above a sunspot that is located at $30^\circ$ from disk center.

Then at $f = 9$ GHz, the $x$-mode at harmonic $s = 3$, we have $\tau \approx 1.4 \times 10^{-9} L_B$.

The lower limit on $L_B$ comes from the observation that the gyroresonance emission at $9$ GHz has $T_B \approx 10^8$ K so that $\tau > 1$. Hence $L_B = B/V_B \approx 7.3 \times 10^8$ cm, or $10^9$. Since the $9$ GHz radiation arises where $f_B = 3$ GHz and $B = 1070$ G, we have $|V_B| \approx 1.5 \times 10^{-6}$ G cm$^{-1}$.

Using this upper limit for $|V_B|$ (which is independent of $f$ and $B$) and starting with the value derived above that the field strength at the base of the corona was $1200$ G, we find that the $f = 3$ GHz level ($B = 360$ G) is $\approx 6 \times 10^8$ cm, or $\sim 8^\circ$, above the base the corona. The scale height of $L_B \approx 10^8$ in is in reasonable agreement with the value $7.5$ obtained by more direct means by Lee et al. (1993a). The agreement can be taken as confirmation that $s = 3$ is the appropriate harmonic to use for determination of the magnetic field strength, as we have done.

Finally, we remark that the lower limit for $L_B$ just derived represents the scale length of magnetic field decrease. Gyroresonance emission at each frequency arises in a much thinner layer: $L \approx 2k_B \rho_0 \cos \theta$. With the parameters used above, the layer where the $9$ GHz radiation arises has a thickness of $\approx 3 \times 10^{-2} L_B \approx 250$ km.

4. DISCUSSION AND CONCLUSION

With the aid of a partial solar eclipse and an X-ray image, we have been able to study the magnetic field as a function of height in the corona above sunspots. The major observed features and conclusions are summarized in the abstract.

There have been several previous studies of magnetic field structure above sunspots. This one is unique in having been observed at many radio frequencies, with high spatial resolution provided by the eclipse, and with an independent measurement of electron density from soft X-rays. The density is important because it constrains at least two aspects of the radio data interpretation—(1) the high-frequency extension of the brightness temperature spectra at the edges of the spots (corresponding to plage sources, we believe), and (2) the vertical gradient of coronal magnetic field at sunspot center. The densities inferred from the radio data are in accord with those derived from the NIXT data.

The comparison of the NIXT image with the distribution of radio emission from this active region (e.g., Fig. 4) underscores the dominance of the magnetic field in the radio emission process. The regions of brightest radio emission in the range 3–10 GHz are associated with regions of the lowest soft X-ray brightness. Such differences demonstrate how the two emission regimes complement one another. Radio emission in the range 3–15 GHz gives virtually the only way of measuring the magnetic field strength in the corona, but quantitative interpretation of the data requires the additional information from other regimes such as soft X-rays. In addition, radio emission from the weaker areas away from sunspots gives constraints on electron density and temperature that are of value in comparing with similar information from soft X-rays and other wavelength regimes.

The active region discussed here differs from those in most earlier studies of gyroresonance radiation in that there is not a single sunspot, but several, and the plage has a more complicated spatial structure. We have developed a simple model involving pairs of sources that vary smoothly in size with frequency, accounting for the observation that the source width increases with decreasing frequency. This model is suggested not only by the appearance of the region in optical photographs, but also because there was clear evidence of pairs of sources in the radio data. The model is able to account for the amplitude and phase behavior of the radio data and also to give a brightness temperature spectrum that agrees in overall magnitude and shape with the gyroresonance spectrum we have come to expect from sunspots.

This work was supported by NASA grant NAGW-3005 and NSF grants ATM-9013173 and AST-8919770 to the California Institute of Technology, and by NASA grant NAGW-1994 to the University of Colorado. The NIXT data were obtained under NASA grant NAG5-626 to the Smithsonian Institution (SI) and this analysis was supported by NSF grant ATM-9191514 to SI.

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