HIGH DYNAMIC RANGE MULTIFREQUENCY RADIO OBSERVATIONS OF A SOLAR ACTIVE REGION

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ABSTRACT

We present high dynamic range, multifrequency radio observations of a solar active region. The evolution of the region is followed at 5 GHz as it rotates from the limb to disk center, and when it is at disk center, observations at 1.5, 5, 8.4, and 15 GHz are used to analyze the distribution of density and magnetic field within the active region. A dynamic range of up to 1500 (at 8.4 GHz) was achieved because these data were well suited to the technique of self-calibration. This high dynamic range allows us to image material at brightness temperatures ranging from 4000 K (above the background) to $1.7 \times 10^6$ K in the same map. We can thus unambiguously identify the signatures of both optically thick gyroresonance emission, outlining magnetic fields, and optically thin thermal free-free emission, indicating density contrast, simultaneously. With data at multiple frequencies we are able to combine both high spatial resolution information from the highest frequency (4" at 15 GHz) with information at larger spatial scales obtained at the lower frequencies. By comparing images at 5 and 8.4 GHz, we are able to identify regions in the trailing part of the active region where optically thin fourth-harmonic gyroresonance emission is contributing to the observed brightness temperatures at 5 GHz, indicating the presence of 450 G fields. Higher fields can be seen in optically thick third-harmonic gyroresonance emission at 5, 8.4, and 15 GHz. We find that the $x$- and $\phi$-mode gyroresonance sources at a given frequency are the same size, implying that they are both third-harmonic emission. This contradicts the usual models in which the $\phi$-mode is not expected to be optically thick at the third harmonic. We measure the variation of the size of the gyroresonance source with frequency, and find an exponential relationship between area and wavelength. An important result is that in comparing higher-frequency emission with the 1.5 GHz image, we find that the 1.5 GHz flux cannot be completely explained by free-free emission and conclude that there is a component of gyroresonance emission at the edges of the active region, where the corona is not opaque due to free-free opacity and there are 140 G fields in the low corona. This result could not be obtained on the basis of the 1.5 GHz map alone.

Subject headings: radiation mechanisms: miscellaneous — Sun: radio radiation — sunspots

1. INTRODUCTION

The basic structure of solar active regions at microwave frequencies has been known for many years. The existence of a "slowly varying component" (SVC) of solar radio emission at a wavelength of 10 cm and its association with active regions was one of the early discoveries of radio astronomy (Covington 1947). Kundu (1959) showed that active regions demonstrate a "core-halo" structure at 3 cm wavelength: emission is the sum of that due to bright compact sources over sunspots, together with more extended but less intense emission assumed to be due to plage. The association of the SVC with active region emission has led to the use of the 10.7 cm solar flux as a standard diagnostic of solar activity (Denisse & Kundu 1957; Kundu & Denisse 1958).

There have, however, been relatively few multifrequency studies of active regions with adequate dynamic range and spatial resolution to explore both the core and the halo structure, simultaneously. The problem has usually been that any observations capable of resolving the core emission are insufficiently sensitive to also image the halo, whose brightness temperature can be a factor of 50 lower at higher frequencies. Furthermore, the interferometers necessary to make high spatial resolution observations often cannot "see" all the extended halo emission because they lack the short-spacing interferometer pairs required. Thus, in studies such as those by Alissandrakis & Kundu (1984; Westerbork observations), Shevgaonkar & Kundu (1984; VLA observations) and Gary & Hurford (1987; VLA plus eclipse observations), the lowest contour in the radio images which can be regarded as reliable is at a level of about 10% of the peak intensity (brightness temperature of roughly $2 \times 10^3$ K). In most active regions, particularly at frequencies above 8 GHz, a large fraction of the halo flux arises from lower intensities than this.

Generally, the core and halo components are thought to arise from different emission mechanisms. Multifrequency observations can be used to test emission mechanisms, since the flux spectrum of thermal bremsstrahlung emission is well known. The core emission is associated with sunspots or with exceptionally strong magnetic fields in plage. It is assumed to be due to gyroresonance emission from the corona (Ginzburg & Zheleznyakov 1961; Zheleznyakov 1962; Kakinuma & Sparrow 1962), and thus outlines a layer of constant magnetic field in the corona (e.g., Hurford 1986). Gyroresonance emission at different frequencies arises from different magnetic field strengths, i.e., different height layers in the corona, and can thus be used to investigate the three-dimensional distribution of magnetic fields in the corona. By contrast, the halo emission probably arises from optically thin thermal bremsstrahlung of dense material in the lower corona, transition region, or chromosphere. Only by observing both components of emission simultaneously can we get a complete picture of the...
radio emission of an active region and thereby model the active region and relate its parameters to the level of the SVC. At longer wavelengths (e.g., 20 cm) the core-halo structure is no longer evident, because thermal bremsstrahlung can be optically thick and produce brightness temperatures equal to those due to gyroresonance opacity.

In this paper we analyze radio observations of a single active region at 0.33, 1.5, 5, 8.4, and 15 GHz carried out with the Very Large Array (VLA) during International Solar Month (1988 September). The VLA was in D-configuration, which is ideal for observing extended structure, at the expense of spatial resolution. By using multifrequency observations we are able to achieve high spatial resolution at high frequencies while simultaneously imaging the weaker extended emission at lower frequencies. The quality of the data at 5 and 8.3 GHz is exceptional. The active region is dominated by a single spot, and the compact radio emission of this spot makes these data particularly good for the technique of self-calibration (e.g., Cornwell & Fomalont 1989). In this way we were able to reduce the noise in the maps by a factor of about 50 compared with the original data. In the final maps the dynamic range (defined here as peak flux divided by the r.m.s. map noise $\sigma$) is up to 1500, so that we can display emission from the 3000 K level ($3\sigma$) to the 1.8 x 10^6 K level in the same map. We compare the images with optical data and find exceptionally good correspondence between them. We also have 5 GHz observations of the same active region on 4 days within 1 week and use these to compare the evolution of the region in radio with its optical evolution.

2. OBSERVATIONS AND ANALYSIS

2.1. Radio Maps

Observations of the Sun with the VLA were carried out by us on 1988 September 11, 12, 13 and 17, for 6–10 hr on each day, during the International Solar Month campaign. A number of different topics were addressed by these observations, and here we report only on the study of AR 5148, the target active region for the SMM International Solar Month campaign at that time. Most of the data we report were taken on 1988 September 17, when we carried out LP (0.33 and 1.5 GHz observations simultaneously), C (5 GHz), X (8.3 GHz), and U (15 GHz) band observations sequentially. The 15 GHz observations have been discussed elsewhere in detail (White, Kundu, & Gopalswamy 1991, hereafter WKG) and will only be summarized here and used where they are relevant at longer wavelengths. At each band except LP (1446 and 333 MHz), two sideband frequencies were recorded (12.5 MHz bandwidth; 4566, 4666; 8234, 8334; 14684 and 14834 MHz), and at each band the two sidebands were combined in the analysis to improve the statistics. The LP observations used disk center as the phase center, while the shorter wavelengths were pointed at the heliographic coordinates S10E02 at 0 UT. The different bands were observed sequentially, and another region of the Sun, not discussed here, was also targeted, so that at any one wavelength only about an hour or less of observing was carried out. However, observations were spaced throughout the day so as to optimize the u-v coverage, and in fact the resulting beams are excellent at all frequencies. We also use 5 GHz data taken in the same way on September 11, 12, and 13.

The data benefited greatly from the techniques of self-calibration, as mentioned above (note that for the maps made here, the amplitudes of the non-solar calibrator antennas were corrected for the known VLA solar calibration problem in the years 1982–1988 using the AIPS program SOLFX written by T. Bastian). Our procedure was to use steps of phase self-calibration, followed by amplitude self-calibration when phase correction produced no further improvement in the maps. Both the initial phase calibration step and the initial amplitude calibration produced dramatic improvements in map quality (i.e., reductions in map noise and hence improvement in the relative contrast of weak features). Our experience with this technique is that it is actually rare for improvements of this magnitude (a factor of up to 50) to be obtained. The data for which improvements were obtained here (5 and 8.3 GHz) are ideal in two respects: (1) they contain a strong compact source containing a significant fraction of the total flux from the active region (the sunspot-associated source); and (2) the VLA was in D-configuration, which is its most compact configuration and hence is most sensitive to extended structure. The contiguous emission from this region covered an extent of up to 200', and only if there are interferometer baselines in the array sensitive to this scale length can one actually benefit from self-calibration. If they are not present, the VLA simply cannot "see" the weak structures which, in the case here, self-calibration was able to bring out from the noise. Only in D-configuration does the VLA have short enough baselines to see 200' structures at either 5 and 8.3 GHz. At 15 GHz, the VLA is nominally insensitive to structures larger than 90', and this effect is seen in our maps. For this reason, self-calibration did not dramatically improve the maps of the active region at 15 GHz, and cannot do so for active regions with an extent in excess of 100'. Similarly, at 1.5 GHz there are numerous sources of similar intensity in the map, rather than a single dominant compact source, and self-calibration, while helpful, does not produce dramatic improvements.

Active-region maps are generally circularly polarized. In order to preserve the integrity of the polarization maps it is necessary to self-calibrate the right–circularly polarized (R) and left–circularly polarized (L) data independently. Tests showed that, as expected, calibration of both types of data using total-intensity (Stokes I) maps resulted in completely spurious circular polarization (Stokes V) maps. The maps shown here resulted from self-calibrating the R and L data separately and combining the final maps to obtain I and V maps. This independent self-calibration of the two data sets provides a test of the self-calibration procedure, in that any inaccuracy in the amplitude calibration is likely to show up as a spurious widespread polarization in the maps. No such effect was seen in these data: the low-level structures (brightness temperatures less than 20,000 K) which were only revealed by the self-calibration procedures generally were identical in the R and L maps, so that they are absent in the V maps. The radio "neutral line" agreed well with the photospheric neutral line from magnetogram data. Significant fluxes of V were only found close to

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1 The Very Large Array is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
the emission peaks, which are thought to be due to gyroresonance emission and hence more likely to be polarized than weaker thermal emission. In fact, when the \( R \) and \( L \) maps were combined, the \( I = 0.5 \ (R + L) \) map did not show a \( \sqrt{2} \) improvement in rms noise whereas the \( V = 0.5 (R - L) \) map showed a factor of 2 or 3 reduction, compared with the rms noise in the \( R \) and \( L \) maps (which were generally very similar in value; see Table 1). This implies that much of the "structure" in the "empty" regions of the maps used to calculate the rms noise was identical in \( R \) and \( L \). This may be due to residual sidelobes of the active region emission, which were not cleaned out, perhaps due to temporal variation; or it may be real structure, such as the network contrast seen by Kundu et al. (1979), Erskine & Kundu (1982), Gary & Zirin (1988), and Gary, Zirin, & Wang (1990). The latter authors show that emission even at the 1000 K level is remarkably well associated with the locations of magnetic fields in BBSO magnetograms. We are unable to determine which effect is responsible, but at any rate the excellent cancellation of the weak emission in the \( R \) and \( L \) maps, while preserving the strong \( V \) emission near the intensity peaks, indicates to us that self-calibration has accurately handled the two data sets despite the difference in the morphology and intensity of most of the \( R \) and \( L \) emission. We note that on September 11 the map rms at 5 GHz is about 30% lower in "empty" regions above the disk than it is in "empty" regions a similar distance from the active region but on the disk, suggesting that some of the residual is real structure.

2.2 Overlays on Optical Data

We have used digitized video magnetograms and off-band \( \text{H} \alpha \) images provided by the Big Bear Solar Observatory (BBSO; courtesy of Alan Patterson) for accurate overlays on the radio data. We also have full-disk magnetograms and \( \text{H} \alpha \) images from Kitt Peak National Observatory (courtesy of J. Harvey), and \( \text{H} \alpha \) and \( \text{Ca K} \) line images from Sacramento Peak (courtesy of L. Gilliam).

The pointing center of the BBSO images is given in terms of right ascension and declination offsets from the apparent disk center, but the vertical and horizontal pixel scales are different. We determined these pixel sizes both from comparison of common features on different BBSO images with different pointing centers, and comparison with Kitt Peak National Observatory full disk magnetograms. Both methods gave the same result: e.g., on 1988 September 17 the raw images had a horizontal pixel length of 0''67 and a vertical pixel length of 0''54. Uncertainties in these sizes are estimated to be only a few percent.

We stretched the BBSO images to a square pixel dimension and then rotated them to bring the solar north pole to the top of the images using routines within AIPS. The relative offsets between the radio and optical images were determined from the nominal pointing at Big Bear and the VLA, and coincident subimages of identical size for the overlays were produced.

<table>
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<th>Date</th>
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<th>Type</th>
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<th>rms ( T_b ) (10^3 K)</th>
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<td></td>
<td>( V )</td>
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<td>21.8 ( \times ) 21.8</td>
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<td>1286</td>
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<td></td>
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<td>947</td>
<td>0.92</td>
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<tr>
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<td>652</td>
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</tr>
<tr>
<td></td>
<td>( L )</td>
<td>5.00 ( \times ) 4.60</td>
<td>34.6</td>
<td>0.6</td>
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</tr>
<tr>
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<td>( R )</td>
<td>50 ( \times ) 50</td>
<td>1838</td>
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<tr>
<td></td>
<td>( L )</td>
<td>50 ( \times ) 50</td>
<td>1668</td>
<td>8.4</td>
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<td></td>
<td>( I ) (MEM)</td>
<td>42 ( \times ) 42</td>
<td>2062</td>
<td>5.0</td>
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</tr>
<tr>
<td></td>
<td>( V )</td>
<td>50 ( \times ) 50</td>
<td>139</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>( R )</td>
<td>209 ( \times ) 188</td>
<td>2863</td>
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<tr>
<td></td>
<td>( L )</td>
<td>209 ( \times ) 188</td>
<td>1567</td>
<td>17</td>
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<tr>
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<td>209 ( \times ) 188</td>
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<tr>
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<td>( V )</td>
<td>209 ( \times ) 188</td>
<td>1114</td>
<td>17</td>
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</tr>
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</table>
Two checks were used to estimate relative pointing errors. On September 11 and 12 the limb is visible in the optical data, and we could compare the expected position of the limb in the radio maps with that in the optical images. On September 11 we found that the optical limb was about 5° east of the radio limb, and on September 12 the error was closer to 9°. We have therefore shifted the optical images for September 11–12 a further 5° to the west to compensate, and the images for September 17 have been shifted 10° west. A second check involves comparison of a depression in the 15 GHz L map with the umbra on September 17 (see below and WKG). This gives the result that the optical image is about 7° east of the radio map, and the image on September 17 has been shifted 7° west and 25° south accordingly.

In the case of the centerline Hα and He I λ 10830 images, we made expanded copies of the active regions from the positive film prints and then produced radio maps at the same scale. Overlays were achieved by comparing features visible in both radio and optical images. These overlays are probably more accurate than most overlays carried out with a similar technique in the past because of the high dynamic range of the radio maps: they contain numerous weak features coincident with small regions of Hα plage distant from the active regions, which are perfect for accurate coalignement. All maps were rotated so that solar north is vertically up. We will proceed by first discussing the evolution of the active region at 5 GHz over the week from 1988 September 11 to September 17, and then discuss the multifrequency data on September 17 when the region was close to disk center.

3. EVOLUTION OF AR 5148 AT 5 GIGAHERTZ

When AR 5148 appeared at a heliographic latitude of 10° south on the east limb, it consisted of a simple leading spot of positive polarity, trailed by a more complex spot of negative polarity. The trailing spot was composed of a roughly continuous and more or less round penumbra, which contained a bright region at its center ringed with a number of small dark pores. This morphology remained for several days, but by September 17 the trailing spot had disappeared, leaving several small dark pores with no penumbra in the region of negative polarity. The leading spot appeared to remain unchanged, but the magnetogram indicates that on September 17 the magnetic field within the umbra is not symmetric: it is strongest in a small region toward the leading edge of the spot. The magnetogram image is actually "burned out" in the region of strongest field in the umbra on September 17, indicating that the umbra was too dark for the measurement of magnetic field (D. Gary, private communication).

Overlays of the I and V radio contours at 5 GHz on the off-band Hα and magnetogram gray-scale images, respectively, for the 4 days are shown in Figure 1. The field of view is 220 arcsec². Map details are given in Table 1. The lowest contour in the radio maps is at a brightness temperature of ±10⁴ K (well above the noise, except for September 11 when the active region was not far from the edge of the primary beam and the primary beam correction has enhanced the noise at the edge of the map). The gray-scale displays in the optical images are chosen simply to show the penumbra and umbra in the off-band Hα images, and the neutral line and regions of strongest magnetic field in the magnetogram. Note that the BBSO magnetogram images use a "wrap-around" technique to display a large dynamic range: thus the dark region within the leading spot on the magnetogram is a region of strong positive field. To determine the polarity of a region one must inspect the boundary between it and the "gray" (low-field) region, which is white in the case of positive polarity (line-of-sight field toward us) and dark for negative polarity. The limb is present in the optical images on September 11 and 12.

In the following descriptions we will quote radio brightness temperatures taken from peaks in either the left–circularly polarized or right–circularly polarized maps as appropriate (i.e., whichever is larger), instead of using the total intensity maps for this purpose. This is because where one mode is optically thick and the other not, the brightness temperature of the optically thick mode actually represents a temperature in the medium and thus has more physical meaning than the value from the I map, which is the mean of the two modes and is not the temperature of any relevant part of the medium.

3.1. September 11

On September 11 the active region is very close to the east limb and the radio maps show a single, relatively smooth source encompassing the two sunspots. The peak emission (at a brightness temperature of 1.0 × 10⁶ K in the R map, but only 8.6 × 10⁴ K in the I map) lies almost exactly midway between the spots in projection (to within the accuracy of the overlay, which is about 2°). Since the beam size is only 15° (Table 1), the emission apparently in front of the leading spot and trailing (or above) the trailing spot is assumed to be real. The extent of the 5 GHz source agrees well with the regions of bright emission seen in the line-center Hα image and the off-band Ca K image. The Ca K image also shows a line of bright emission extending along the limb to the south of the active region, again as seen in the radio map. The peak brightness temperature in this ridge of emission, not associated with strong fields in the magnetogram, is about 40,000 K, and it is unpolarized. The emission above the limb to the north-east is noise amplified by the primary beam correction.

The polarization of the active region is somewhat peculiar. There is a small region of negative polarity in front of the leading spot (marked with a dash; due to the underlying gray-scale image, the breaks in the contours here do not show up distinctly), where the magnetogram shows positive polarity, and a null almost coincident in projection with the leading spot. There is positive polarity peaking at a brightness temperature of about 2 × 10⁵ K and extending from northeast (upper left) to southwest. Limbward (to the southeast) is another region of weak negative polarity. The actual degree of polarization at the peak of the I' map is only about 20%, whereas it rises to 50% on both sides of the I peak within the positively polarized region. The negative polarity reaches only a 20% polarization.

3.2. September 12

By September 12, two distinct emission peaks corresponding to the two sunspots can be clearly seen. In projection they lie very close to the sunspots, so that if we assume that the two sources each lie directly above the corresponding sunspots they

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Fig. 1.—Overlays of 5 GHz VLA images of AR 5148 on BBSO optical images for 1988 September 11, 12, 13, and 17. Figures 1a, 1c, 1e, and 1g show the 5 GHz total intensity brightness temperature contours overlaid on the off-band Hα gray-scale image on September 11, 12, 13, and 17, respectively. Figures 1b, 1d, 1f, and 1h show the 5 GHz circular polarization brightness temperature contours overlaid on the gray-scale magnetograms for September 11, 12, 13, and 17, respectively. The contour interval is $10^4$ K in all maps; contours are at multiples of $-3, -2, -1, 1, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 32, 40, 48, 56, 64, 80, 96, 112, 128,$ and 160 of the interval in the total intensity maps and at multiples of $-32, -24, -20, -16, -12, -10, -8, -6, -4, -3, -2, -1, 1, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 32, 40, 48, 56$ and 64 in the circular polarization maps. The negative contours in the V maps are indicated by broken contours, but they are difficult to distinguish in the gray-scale format. In all cases the dominant emission is positively polarized, and all contours separated from the dominant peak by nulls are negative contours. We mark the negative contours in Fig. 1b by a dash. The solar east limb is visible in the images on September 11 and 12. The field of view is 220° in all images.
Fig. 1—Continued
appear to be at very low heights in the corona. However, the separation of the two radio peaks is somewhat less than the separation of the sunspot centroids, and as we discuss below it is unlikely that the radio sources do lie over the sunspots. The angle between the line of sight and the field lines will also play a role in the projected location (see § 6 below). There is again considerable extended emission present, coinciding with material present in the He I λ10830 images. The peak brightness temperature is 9.6 × 10^5 K in the leading spot source: this value is essentially identical to the peak on September 11. The peak in the trailing source is 8.8 × 10^5 K.

The V map also shows two peaks, but they are of the same polarity even though the underlying photospheric fields are of opposite polarity. This effect is usually attributed to mode coupling and will be discussed further below. The source associated with the leading spot is kidney-shaped, as it was on September 11, but with the leading negative emission now at a magnitude below the 10^4 K level. The trailing source has two peaks within it, aligned along the ridge of strongest magnetic field in the trailing spot. On this day the degree of polarization within the region is relatively uniform, at about 25%.

3.3. September 13

On September 13 the same two sources are visible in the 5 GHz map, but now the source associated with the leading spot has a peak almost 20" away from the umbra. This shift is much too large to be associated with the uncertainty in the overlay of radio on optical data, which is however uncertain on this day because we have no independent checks (see previous section). Again we note that the separation of the two main radio peaks is much less than the separation of the sunspots. The trailing 5 GHz source now appears to be directly along the line of sight to the trailing sunspot. Ridges of emission extending to the north, south, and southwest within the trailing spot line up well with similar ridges of bright emission in the line-center Hα image. The peak brightness temperature is now 1.30 × 10^6 K in the trailing radio source but remains at only 9.7 × 10^5 K in the leading spot source.

The V map again shows two positively polarized sources. However, with the region now on the disk the leading source is no longer kidney-shaped. The trailing source remains elongated north-south, with two peaks being present within it. The degree of polarization is again fairly uniform over the whole region, being 25%–35%.

3.4. September 17

By September 17 the region has changed considerably, in that the trailing penumbra has disappeared, leaving a trailing region of negative magnetic polarity containing only a few weak pores. The radio I map has also changed considerably, although perhaps not as dramatically as the optical image. The trailing source is now much smaller and weaker than the leading source, whereas on September 13 it was stronger and bigger. We can again see that the 5 GHz peak lies well behind the leading sunspot (the region, at about S10W07, is close to disk center and therefore height projection effects are minimal). The peak brightness temperature in the leading source is now 1.61 × 10^6 K, and emission at a temperature in excess of 10^6 K covers an area of about 50" dimension (in the R map). The peak over the trailing area is at 7.5 × 10^5 K. Again ridges of quite strong emission in the radio map align well with bright emission seen in optical images.

The difference between the September 13 and September 17 data is most striking in the V maps, where instead of two positively polarized sources we find that the leading source is positively polarized while the trailing source is negatively polarized, in good agreement with the neutral line in the magnetogram. The dominant leading source contains two peaks, roughly straddling the rear of the sunspot. The negative polarity is relatively compact.

The map of degree of polarization is now more complex than on previous days. The region of the I peak is actually only weakly polarized (about 15%–20%), but there is a region of up to 50% polarization at the leading edge of the I source, to the south of the spot. The trailing emission peak is more highly polarized, at about 35%–40%.

4. MULTIFREQUENCY OBSERVATIONS ON SEPTEMBER 17

4.1. 15 GHz Observations

Overlays of the 15 GHz R and L images on the off-band Hα pictures are presented in WKG. In Figure 2 we present contour plots of the active region in both total intensity and circular polarization at 15, 8.3, and 5 GHz. The field of view is the same in all maps. The bottom contour in each map is at about the 3σ level of the I map. Note that primary beam corrections have not been made for the maps in Figure 2. The 15 GHz observations on September 17 have been discussed in detail by WKG. Over the sunspot there are peaks in both R and L maps, but their brightness temperatures differ considerably: 7 × 10^5 K for the R peak but only 36,000 K for the L peak. The interpretation is that the R map shows an optically thin gyros-mode source due to third-harmonic opacity from 1800 G magnetic fields in the corona, while the brightest peak in the L map shows optically thin free-free emission from cool dense material at the base of a sunspot plume (features at about 2 × 10^5 K seen above sunspots in Skylab UV observations; Foukal et al. 1974). The L peak is offset by 4" toward the umbra from the R peak, consistent with this picture. WKG argued that the magnetic field above the sunspot is not dipole-like as suggested by the magnetogram, but rather that the field seems to be concentrated in a compact loop extending eastward from the spot toward the negative polarity region of the magnetogram.

Toward the trailing end of the active region is a ridge of emission which is brighter than 12,000 K and contains within it several peaks, the brightest of which reaches 33,000 K. Some of these peaks are close to the pores trailing the sunspot, but not more than one of the peaks can be made coincident with the pores by a simple translation of the radio map with respect to the optical, so we cannot make a direct association of this ridge of emission with the line of pores. Negative lobes surround the active region in the L map because it was too large for the VLA to measure all the flux present. A number of the pores lie in these negative lobes. Note that a quiet Sun temperature of about 11,000 K should be added to the values measured in the VLA maps to adjust to true brightness temperatures (e.g., Zirin, Baumert, & Hurford 1991). A deep hole appears in the L map over the umbra, indicating low-density material there.
Fig. 2.—Images of AR 5148 on 1988 September 17 at 15 GHz in \( L \) (top left panel) and \( R \) (top right panel), 8.3 GHz in \( I \) (middle left panel) and \( V \) (middle right panel), and 5 GHz in \( I \) (bottom left panel) and \( V \) (bottom right panel). The field of view is the same in all maps (156° square). The contours in the \( L, R, \) and \( I \) maps are at multiples of \(-4, -3, -2, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 32, 40, 48, 64, 80, 96, 128, 160, 256, 384, 512, 640, 768 \) and \( 896 \) times \( 1000 \) K in the 15 GHz \( L \) map, \( 2 \times 10^5 \) K in the 15 GHz \( R \) map, \( 1500 \) K in the 8.3 GHz \( I \) map, and \( 2500 \) K in the 5 GHz \( I \) map, respectively. The contours in the \( V \) maps are at multiples of \(-48, -32, -24, -20, -16, -12, -10, -8, -6, -4, -3, -2, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 32, 48, 64, 96, 128, 192, \) and \( 256 \) times \( 1500 \) K in the 8.3 GHz map and \( 2500 \) K in the 5 GHz map. A solid dot marks the location of the 15 GHz \( R \) peak in all panels except the 15 GHz \( R \) map itself (in the 15 GHz \( L \) map the dot lies on a region of closely spaced contours and is not readily apparent). The peak temperatures are 36,000 K in the 15 GHz \( L \) map, \( 7.0 \times 10^5 \) K in the 15 GHz \( R \) map, \( 1.3 \times 10^6 \) K in the 8.3 GHz \( I \) map, \( 5.4 \times 10^5 \) K in the 8.3 GHz \( V \) map, \( 1.5 \times 10^6 \) K in the 5 GHz \( I \) map, and \( 2.3 \times 10^5 \) K in the 5 GHz \( V \) map. The beam is \( 50 \times 45' \) in the 15 GHz maps, \( 973 \times 878' \) in the 8.3 GHz maps, and \( 149' \times 141' \) in the 5 GHz maps. The 15 GHz \( L \) map shows negative emission surrounding the active region source, indicating that some emission was present on scales larger than could be mapped with the shortest baseline in the VLA's D-configuration. The blank area along the bottom edge of this panel contained noise which has been greatly amplified by the primary beam correction and has been omitted from the figure.

4.2. 8.3 GHz Observations

The 8.3 GHz maps have a dynamic range of about 1500 (Table 1), which is exceptional for solar data. For reference purposes we have placed a solid dot in each map in Figure 2 at the location of the peak in the 15 GHz \( R \) map. Thus one can clearly see that the 8.3 GHz peak is displaced eastward of the 15 GHz peak. The peak is eastward of the sunspot umbra by about \( 10' \), and is clearly not symmetric about the umbra. The 8.3 GHz map is dominated by a compact source close to the sunspot, which has a peak brightness temperature (in the \( R \) map) of \( 1.74 \times 10^6 \) K. However, this source does not lie over the sunspot, and the actual brightness temperature over the umbra is quite low. The same ridge visible in the 15 GHz \( L \) map is also present in the 8.3 GHz map, with a brightness temperature of around \( 50,000 \) K. There are also two much...
fainter extensions protruding to the south, which have temperatures of only about 8000 K. All of these features have identifiable bright counterparts in the line-center Hα image and the He I λ10830 images (see § 5 below). In the vicinity of the eastern southern extension, a short filament appears in the line-center Hα image and a corresponding bright channel is present in the He I λ10830 image. There is a hole in the active region emission at the corresponding location in the 8.3 GHz map (marked “J” in Fig. 3). In this region of the map emission at 4000 K would be statistically significant, and thus we might expect to see thermal free-free emission from the filament transition region if it were optically thick.

The polarization map shows a strong positive peak associated with the strongest emission, and two weak negative peaks over the opposite photospheric polarity. When we overlay the 8.3 GHz maps on the 15 GHz L map we find that these two negative peaks coincide exactly with two of the peaks in the ridge of emission in the 15 GHz L map. The other peaks in the 15 GHz L map do not show any polarization. The coincidence of features in the independent 8.3 and 15 GHz maps gives us further confidence that the calibration techniques used to produce high dynamic range in the 8.3 and 5 GHz maps has not produced spurious features. We note that the two negative peaks are at a level 240 times weaker than the peak in the 8.3

![Image of AR 5148 on 1988 September 17 at 8.3 GHz in I (top left panel) and V (top right panel), 5 GHz in I (middle left panel) and V (middle right panel), and 1.5 GHz in I (bottom left panel) and V (bottom right panel).](image)

Fig. 3.—Images of AR 5148 on 1988 September 17 at 8.3 GHz in I (top left panel) and V (top right panel), 5 GHz in I (middle left panel) and V (middle right panel), and 1.5 GHz in I (bottom left panel) and V (bottom right panel). The field of view is the same in all maps (324" square). The contours in the I maps are at multiples of -4, -3, -2, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 32, 40, 48, 64, 80, 96, 128, 160, 256, 384, 512, 640, 768, and 896 times 1500 K in the 8.3 GHz map, 2500 K in the 5 GHz map, and 15,000 K in the 1.5 GHz map, respectively. The contours in the V maps are at multiples of -48, -32, -24, -20, -16, -12, -10, -8, -6, -4, -3, -2, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 32, 40, 48, 64, 96, 128, 192, and 256 times 1500 K in the 8.3 GHz map, 2500 K in the 5 GHz map, and 15,000 K in the 1.5 GHz map. The beam is 50" × 50" in the 1.5 GHz maps. Letters in the 8.3 GHz I map indicate optically identified features also marked in Fig. 5 and discussed in § 5.
GHz R map, and without high dynamic range we would be unable to identify them.

We identify the strong peak as a sunspot-associated source and call the remaining emission from the region the "plage" emission. The flux from the spot source in different maps is given in Table 2, along with Gaussian fits to the source size. At 8.3 GHz the flux from the spot source clearly dominates the total flux from the region, and the spot contribution is much greater in the R map than in the L map, whereas the plage contributions are roughly the same in all maps. The size of the spot source in the R map is also much larger than the size of the source in the L map. The peak in the 8.3 GHz V map is well to the north of the R peak, because the L map has a kidney shape with a hole in its north edge which the R map does not show. The degree of polarization at the R peak is 37%, but polarization rises rapidly to the north of the R peak and reaches a value of 80% at the location of the peak in the V map, where the brightness temperature in R is 4.9 × 10^5 K. The degree of polarization in the negative peaks is actually quite small: each is only about 12% polarized.

4.3. 5 GHz Observations

The 5 GHz maps in Figure 2 show that the distinction between the "spot" source and the "plage" source is now much more difficult to make than at 8.3 GHz. The ridge of bright emission eastward of the spot is at a brightness temperature of about 7 × 10^5 K, compared with the value of 50,000 K at 8.3 GHz. One can also see from Table 2 that the difference between the two polarizations is much smaller than at 8.3 GHz. The level of emission over the umbra is again low, while the brightness temperature gradient there is large. The southerly extensions are again present, but are somewhat brighter than at the higher frequency (20,000–40,000 K). As mentioned above, the V map shows that these extensions are largely unpo-

4.4. 1.5 GHz Observations

Figure 3 shows the 8.3, 5 and 1.5 GHz I and V maps of the active region in a wider field of view. In these maps the presence of emission from a weak but growing region south of AR 5148 can be seen at all frequencies. The 1.5 GHz I map is relatively featureless, and the peak is shifted further eastward than at higher frequencies. The emission from the southern region shows up as a quite strong ridge at 1.5 GHz. The peak brightness temperature in AR 5148 reaches 1.84 × 10^6 K (in the R map), which is in excess of the temperatures seen at higher frequencies. The 1.5 GHz emission covers a much larger area also. The total flux at 1.5 GHz is therefore only slightly lower than at 5 GHz (Table 2). We are unable to distinguish between plage and spot sources at 1.5 GHz.

The 1.5 GHz V map preserves the polarity structure seen at higher frequencies, with a simple bipolar structure. However, the orientation of the axis of the V source is at an angle to the corresponding axis at higher frequencies. In fact, as we proceed from 8.3 to 5 to 1.5 GHz, the line joining the center of the positive emission in the V map to the center of the negative emission rotates in a clockwise fashion. The ridge over the southern region is weakly positively polarized.

The 1.5 GHz maps taken during 1988 September will be discussed more extensively elsewhere (Gopalswamy, White, & Kundu 1991).

4.5. 0.33 GHz Observations

Figure 4 shows a yet larger field of view as observed at 1.5 and 0.33 GHz. AR 5148 appears as a bipolar source at 0.33 GHz, which is the remnant of a decaying noise storm also observed on 1988 September 11, 12, and 13 (when it was approximately 100 times as intense). The point of this figure is twofold: it clearly shows that the polarization of the 0.33 GHz noise storm emission is reversed relative to the 1.5 GHz emission, which is exactly as expected since the emission mechanism should change from thermal bremsstrahlung at 1.5 GHz, polarized in the sense of the x-mode, to plasma emission at 0.33 GHz, dominated by the e-mode. We note that the noise storm emission is really quite weak (Table 1) and might be mistaken for a metric slowly varying component if we did not have observations earlier in the week; if the spatial resolution of the observations were higher, it is likely that the peak brightness temperatures associated with the noise storms would be higher (White, Thejappa, & Kundu 1991).

The second point is that the bipolar noise storm presumably outlines the two legs of a coronal magnetic structure high in the

<table>
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<th>Wavelength (cm)</th>
<th>Data Type</th>
<th>Total Flux (sfu)</th>
<th>&quot;Plage&quot; Flux (sfu)</th>
<th>&quot;Spot&quot; Flux (sfu)</th>
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Corona above the active region. It is of great interest that the leading component of the bipolar noise storm is well in front of the sunspot, although there is no magnetic field in the photosphere in front of the sunspot, nor any 1.5 GHz emission indicative of lower lying loops. This gives the impression of a large loop with its feet close together in the active region and its legs diverging as its height increases. The axis of the noise storm is at a different orientation from the 1.5 GHz axis, and in fact has rotated back anticlockwise.

One useful aspect of the 0.33 GHz observations is that they tell us the plasma density. Conventionally noise storm continuum emission is assumed to be at the fundamental of the plasma frequency (Elgaroy 1977; Kai, Melrose, & Suzuki 1985), and thus the noise storm sources represent a density of \( 1.3 \times 10^9 \) cm\(^{-3}\). Refraction tends to shift the apparent height of noise storm sources upward in the corona (Melrose 1973), but that should not affect a source close to disk center. What we can say is that the noise storm observations provide a constraint on the density at lower heights in the corona (relevant to sources at higher frequencies), which must exceed \( 1.3 \times 10^9 \) cm\(^{-3}\).

5. COMPARISON OF RADIO IMAGES WITH \( \text{H}\alpha \) AND \( \text{He}\;\text{I}\;\lambda\;10830 \) IMAGES

One advantage of having high dynamic range radio maps is that we can do a careful comparison of weak radio features distant from the active region center with corresponding weak optical features, thereby allowing accurate coalignment of radio and optical data. Gary & Zirin (1988) and Gary et al. (1990) have demonstrated this well in 8 GHz observations of quiet regions of the solar surface where no sunspots (and hence no emission at coronal temperatures) were present. In Figure 5 (Plate 15) we show expanded views of the region around AR 5148 in (a) centerline \( \text{H}\alpha \) (courtesy of Sacramento Peak Observatory) and (b) \( \text{He}\;\text{I}\;\lambda\;10830 \) (courtesy of Kitt Peak National Observatory), respectively (the scale in the \( \text{H}\alpha \) image is about 10% larger, in arcsec per mm, than the scale in the \( \text{He}\;\text{I}\;\lambda\;10830 \) image).

Bright features in the \( \text{H}\alpha \) image are generally assumed to be plage, i.e., regions of high-density material at chromospheric temperatures. Dark features in the \( \text{H}\alpha \) image nearly all consist of cool filamentary material (the one exception is the sunspot). Both \( \text{H}\alpha \) and \( \text{He}\;\text{I}\;\lambda\;10830 \) are chromospheric lines, but the \( \text{He}\;\text{I}\;\lambda\;10830 \) image mostly shows absorption features due to excitation of chromospheric \( \text{He} \) by coronal EUV and soft X-ray emission, and it is regarded more as a tracer of coronal emission. Therefore the dark features in a \( \text{He}\;\text{I}\;\lambda\;10830 \) image are interpreted as either regions of the chromosphere where absorption of emission from the solar disk is high due to high density coronal material immediately above irradiating the chromosphere, or else filamentary material which is dense enough to provide absorption. The latter can be identified by comparison of the \( \text{H}\alpha \) and \( \text{He}\;\text{I}\;\lambda\;10830 \) images. Regions which
Fig. 5. — The (a) centerline Hα image and (b) He I λ10830 image of AR 5148 on 1988 September 17. Letters indicate optical features discussed in the text.
are light in He i λ10830 are thought to represent regions of very low density in the corona which produce little EUV radiation, such as coronal holes or filament channels.

We have labeled various features in the Hα and He i λ10830 images of AR 5148 (Figs. 5a and 5b). The location of the spot S (see Fig. 1 for the magnetogram and off-band Hα images) is readily apparent in Hα, but not in He i λ10830. We have labeled a number of regions of bright plage (the linear plage features A, B, C, E, F; the compact features D, I; and the long ridge prominent in the 15 GHz L map, R), each of which shows up in both Hα (as a bright feature) and He i λ10830 (as a dark feature). We have also marked two dark features in the He i λ10830 image which have no correspondence in Hα: the dark blob G, and the set of coronal loops H.

We find that nearly all the labeled optical features have clearly identifiable counterparts in the regions of the 5 and 8 GHz radio maps which we are attributing to optically thin thermal bremsstrahlung, and thus serve as density indicators (note that many of these features are close to the edge of the primary beam at 15 GHz and thus we do not expect to see them in the 15 GHz maps). Most of the labeled plage features show up as peaks (A, C, D, F, I in the 8 GHz map) or unmistakable ridge features (H, B) in the radio maps. An exception is the plage feature E, which shows no obvious radio emission. Nearby is the only obvious filamentary material near the active region (labeled J in the Hα image), which shows up as a depression cutting into the main body of radio emission from the active region.

We also note the ridge of emission extending to the north from the main body of active region emission in the 5 and 8 GHz maps. This corresponds well in location to the set of loops H in the He i λ10830 image, which run in a northeasterly direction. It is not clear what these loops represent, since any high coronal loops are not expected to produce a sharp feature through their radiation onto the chromosphere. Thus we must interpret these as coronal loops which are almost horizontal, so that their tops lie just above the chromosphere. The apparent distance between the loop top and a line on the photosphere joining the footpoints is about 24,000 km, whereas the height of the chromosphere is only about 2000 km. Alternatively these He i λ10830 loops may represent high-density loops in the corona which are themselves absorbing the disk emission. The interesting feature of these loops is that the radio observations show only emission from the footpoints (seen in both 8 and 15 GHz maps), and the He i λ10830 image also indicates that the highest densities in the loops occurs there. This suggests that the material producing the emission is highly concentrated at the footpoints.

The close correspondence between the Hα and the He i λ10830 and radio images is yet another example of the result that high density in the photosphere (Hα) is also a good indicator of high density in the corona (He i λ10830 and radio).

6. IDENTIFICATION OF EMISSION MECHANISMS

When the radio data are excellent, as is the case here, we can identify emission mechanisms without the need to consider typical coronal parameters as is usually done. This is because the flux spectrum of optically thin thermal bremsstrahlung is flat, and so it can be easily identified; remaining emission at coronal temperatures is almost certainly due to gyroresonance emission. In this section we use comparison of maps at different frequencies in order to identify emission mechanisms at different locations; first, we briefly summarize the properties of the two relevant emission mechanisms, thermal gyroresonance and thermal bremsstrahlung, in order to have a basis for interpreting the observations.

6.1. Opacity Formulae

We adopt the following formula for gyroresonance opacity (per centimeter), derived from the general expression for single-particle gyromagnetic emissivity in Melrose (1980):

$$k(s, f, \theta) = \left( \frac{\pi^{3/2} f^2 \frac{\mu}{fc} \sqrt{1 - \sigma \cos \theta}}{s!} \left( 1 - \sigma \cos \theta \right)^{s^2} \left( \frac{2}{s!} \right)^{s^2} \frac{\sin^2 \theta}{\cos \theta} \right)^{s-1} \exp \left[ -\frac{\mu}{2 \cos^2 \theta} \left( 1 - \frac{\Delta f_k}{f} \right)^2 \right],$$

where $s = \text{harmonic number}$, $f = \text{frequency}$, $f_k = \text{plasma frequency}$, $\mu = mc^2/k_BT$ is an inverse temperature variable, $\theta$ is the angle between the magnetic field and the line of sight, and $\sigma = -1$ refers to the extraordinary (x) mode while $\sigma = +1$ refers to the ordinary (o) mode. This equation is valid in the limit

$$|a| < 1, \quad a = \frac{f_k \sin^2 \theta}{2f \cos \theta}$$

and hence not strictly valid at the low harmonics of interest here, or at angles of propagation close to normal. However, for the following qualitative discussion this detail is not important. In this equation the amplitude of the wave varies as $e^{-\alpha x}$. A number of different numerical constants in forms of equation (1) appear in the literature, apparently due to differing definitions of the opacity parameter $\kappa$ (e.g., Lang 1980; Melrose 1980; Dulk 1985).

In actual applications, the gyroresonance layer at a particular harmonic and frequency is so thin that we are only interested in the opacity of the layer. This may be obtained by assuming a linear variation of the magnetic field in the gyroresonance layer along the line of sight (scale length $L_B = B/|\partial B/\partial l|$ evaluated in the layer) and carrying out an integration along the line of sight. We find that the opacity is

$$\tau(s, f, \theta) = \frac{\pi^{3/2} f^2 \frac{\mu}{fc} \sqrt{1 - \sigma \cos \theta}}{s!} \left( 1 - \sigma \cos \theta \right)^{s^2} \left( \frac{2}{s!} \right)^{s^2} \frac{\sin^2 \theta}{\cos \theta} \right)^{s-1} \exp \left[ -\frac{\mu}{2 \cos^2 \theta} \left( 1 - \frac{\Delta f_k}{f} \right)^2 \right].$$

The thermal width of a cyclotron line at coronal temperatures implies that $B$ varies by less than 1 G across the gyroresonant layer, for typical magnetic gradients in the corona.

The formula for thermal bremsstrahlung is well known, but in the limit of frequencies close to low harmonics of the gyrofrequency, the usual approximations are not always accurate. Assuming that the plasma frequency is much less than the observing frequency (i.e., density $< 1.24 \times 10^9 f_{GHz}^2 \text{ cm}^{-3}$),
we find the following (Melrose 1980), again in the limit \(|a| \ll 1\):

\[
\kappa(f, \theta) = 9.78 \times 10^{-3} \frac{n^2}{f^2 T_{\rm 15}} \left[ 1 + \frac{a f_0 \cos \theta}{f(1 + \alpha^2)} \right]^{-2} \times (24.2 + \ln T - \ln f) \quad (4)
\]

when \(T > 1.6 \times 10^5 \) K.

6.2. Characteristics of Gyroresonance Emission

The expected properties of gyroresonance emission from the magnetic geometries expected above sunspots have been widely discussed in the literature (e.g., Lantos 1968; Gelfreikh & Lubyshev 1979; Alissandrakis, Kundu, & Lantos 1982; Hurford 1986; Brosius & Holman 1989), and we summarize them only briefly here. For nonrelativistic temperatures the parameter \(\mu\) is large (4000 at a temperature of \(1.5 \times 10^5 \) K) and the opacity decreases dramatically from one resonant layer to the next. For this reason is optically thin emission is generally ineffective (unless no harmonic is optically thick in the corona) and only the highest optically thick layer at a given frequency is of interest. This is a surface of constant magnetic field, and we usually assume constant temperature in this layer. The density may vary across the layer from typical quiet region values of \(2 \times 10^{10} \) cm\(^{-3}\) to soft X-ray loop values of \(2 \times 10^{10} \) cm\(^{-3}\). However, changes in density do not play any significant role while the gyroresonant layer remains optically thick, since the brightness temperature stays equal to the kinetic temperature. The angle \(\theta\) will also vary, and this is probably the most important effect. According to equation (1), the opacity vanishes at \(\theta = 0\), implying that there should always be an optically thin “hole” in the gyroresonant layer where we look along the magnetic field. This hole can, however, be “filled in” if we can see through it to the second-harmonic layer and if that layer lies in the corona. Since the ratio of \(\delta\)-mode opacity to \(x\)-mode opacity is

\[
\left( \frac{1 - \cos \theta}{1 + \cos \theta} \right)^2 \approx \frac{\theta^4}{16} \quad (5)
\]

at small \(\theta\), the hole at \(\theta = 0\) at a given harmonic will be much bigger in the \(\delta\)-mode than in the \(x\)-mode. In fact, since even at \(45^\circ\) the \(\delta\)-mode opacity is only 4% of the \(x\)-mode opacity, numerous authors have concluded that the \(x\)-mode can be optically thick in the corona at the third harmonic for typical parameters, while the \(\delta\)-mode can only be optically thick at the second harmonic. Since the second-harmonic layer for a given frequency will be smaller than the third-harmonic layer, the \(\delta\)-mode source should be much smaller than the \(x\)-mode source. Thus the circular polarization map of a source near disk center, as on September 17 in this case, should show a ring structure, with the \(x\)-mode dominating at the inside edges of the ring and the \(\delta\)-mode at the outer edges. On the other hand, if both modes are optically thick at the same harmonic, then since the opacities of the two modes becomes more equal as \(\theta\) increases, the \(x\)-mode will dominate the inner part of the ring, while the outer part should be unpolarized.

The effects of the convolving beam size can also greatly affect the appearance of sources. In particular, rings which are smaller than about 30° in dimension will not show a depression with a 15° beam such as was available for the 5 GHz observations here, but rather a disklike structure with a peak brightness temperature depressed because of the contribution of the hole. We believe that this is not the case here because of the distance of the 5 and 8.3 GHz peaks from the sunspot umbra, which makes it unlikely that any ring structure is present. The similarity in the peak temperatures at the two frequencies also suggests to us that they are true coronal temperatures from an optically thick source. However, we note that due to beam convolution effects the \(\delta\)-mode map can show a lower peak \(T_b\) even when both modes are optically thick, if the source is barely resolved at both modes but the \(\delta\)-mode is optically thick in a smaller area.

6.3. Map Comparisons at Adjacent Frequencies

In Figure 6 we present a map of the ratio of the 15 GHz \(L\) flux to the 8.3 GHz \(L\) flux, minus unity. The field of view is the same as in Figure 2. The 15 GHz data were convolved with the 8.3 GHz beam and regridded before producing this map; the ratio was only calculated where the flux in both maps exceeds 0.009 sfu per beam. We have subtracted unity for the purposes of display: thus where the flux is identical at the two frequencies, the map should show zero. Negative values in the map indicate where the 15 GHz flux is below the 8.3 GHz flux, which is the case almost everywhere. However, along the ridge extending eastward from the spot the map shows values very close to zero, so that the 15 and 8.3 GHz fluxes are essentially

![Plot of the ratio of the 15 GHz L flux to the 8.3 GHz L flux, minus unity, in the same field of view as in Fig. 2. The 15 GHz data have been convolved with the 8.3 GHz beam and both images have had primary beam corrections made before calculating the ratio. The ratio is only plotted where the flux exceeds 0.009 sfu per beam. Contours are at \(-0.8, -0.6, -0.4, -0.2, -0.05,\) and 0.05. Most of the ridge in the 15 GHz map shows a value near zero in this plot, indicating that the 15 and 8.3 GHz fluxes are identical.](image-url)
identical throughout the ridge. This holds true even at the locations of the peaks in the 15 GHz map. The flux ratio decreases greatly close to the sunspot where we argue that the 8.3 GHz flux is dominated by gyroemission.

In Figure 7 we present the ratios of the 8.3 GHz flux to the 5 GHz flux (minus unity) for both R and L polarizations, after regridding the 8.3 GHz maps and convolving them with the 5 GHz beam. The field of view is the same as in Figure 3, and again we have only plotted points where the flux exceeds 0.009 sfu. Both R and L maps show the same pattern: the 8.3 GHz flux is much larger than the 5 GHz flux near the emission peaks (a factor of 2 larger in the L ratio and 3 larger in the R ratio); this peak is then surrounded by a ring, distended toward the neutral line, where the 5 GHz flux exceeds the 8.3 GHz flux; and at the trailing end of the ridge of emission the 8.3 GHz flux is again larger than the 5 GHz flux. There are no extended regions where the flux ratio is unity (map values close to zero), in contrast to Figure 6.

These features are interpreted as follows. Since the emission peaks in the 8.3 and 5 GHz maps are at the same coronal brightness temperatures, the 8.3 GHz flux should be a factor of 2.94 greater than the 5 GHz flux. We find a peak ratio of 3.0 in the R map, which is exactly consistent with this. We believe that the peak ratio in the L map is only 2 because the emission is not optically thick there. The ring surrounding the peak where the 5 GHz flux exceeds the 8.3 GHz flux is due to the fact that the 5 GHz emission comes from the 600 G layer, which has a larger area than the 1000 G layer where the 8.3 GHz flux originates.

In most of the ridge the 5 GHz flux exceeds the 8.3 GHz flux: since we know that the 8.3 GHz flux is optically thin bremsstrahlung, it follows that some other effect is contributing at 5 GHz. We argue that this is optically thin gyroresonance emission. The peak brightness temperature excess in the 5 GHz map is about $4 \times 10^5$ K. The degree of polarization at this location in both the 8.3 and 5 GHz maps is low, so we argue that we can set the angle between the magnetic field and the line of sight equal to 90°. Third-harmonic emission at $T = 1.7 \times 10^6$ K with a plausible magnetic scale length would be optically thick, and in addition would require 600 G fields in the ridge. If instead we consider the fourth harmonic, we require $nL_B = 1.3 \times 10^{19}$ cm$^{-2}$. This can be achieved for a plausible scale length and density, e.g., $L_B = 3 \times 10^5$ cm and $n = 4 \times 10^9$ cm$^{-3}$. The resulting value for the density is consistent with the value deduced in the same location by WKG based on the free-free emission at 15 GHz. We conclude that optically thin emission from 450 G fields is contributing in the ridge portion of the map.

The region of 5 GHz excess extends further to the east in the L map than it does in the R map, implying that the x-mode opacity is in excess of the o-mode opacity there (where the photospheric field is downgoing). We are unable to explain the brightness temperature excess in the 8.3 GHz emission at the end of the ridge, which amounts to 15,000 K.

Since we can clearly identify the gyroresonance and free-free contributions to the emission at different frequencies, it is instructive to plot their spectra. The values of the flux from the “spot” or gyroresonance source, from the “plage” or free-free source, and the total flux are given in Table 2 and plotted in Figure 8. Total fluxes were obtained simply by integrating over the box in each map which includes the emission from AR 5148 evident in Figure 2 (excluding the emission seen in features connecting AR 5148 to regions further south). The “spot” flux was obtained by fitting a Gaussian to the peaks in the appropriate maps, using a fitting box which only included the flux which seemed to be due to gyroresonance emission. The 1.5 GHz total fluxes given are the peak fluxes resulting from a Gaussian fit to the peak in the map, using a box which was effectively the same size as that used at 5 GHz. The total flux in this box was about 10% less than the peak flux resulting from the Gaussian fit, but we have used the latter to allow for the effects of the larger beam at 1.5 GHz. We have set the 15 GHz “plage” flux in Figure 8 to 0.9 sfu in order to correct for the missing flux at large spatial scales, which we can estimate from the 8.4 GHz data to be about 0.3 sfu. At 5 GHz the “spot” flux includes the contributions from both the strong source closest to the spot and the assumed gyroresonance emission responsible for the negatively polarized feature near the neutral line (the size quoted only includes the source near the spot, however). The “plage” flux at 5 GHz includes the...
deduced optically thin gyroresonance contribution from the ridge, but this is small. The flux spectrum drops sharply from 8.4 to 15 GHz, mostly because the size of the "spot" source decreases sharply.

There is one anomaly in the flux spectrum, however. The point at 1.5 GHz is assumed to be largely due to optically thick thermal free-free emission, and as such its value should not exceed the optically thin thermal free-free flux seen at higher frequencies (e.g., see the curves in Dulk 1985). Even when one takes into account the fact that the 1.5 GHz source is larger than the free-free sources at higher frequencies, the flux at 1.5 GHz is larger than one can explain via optically thick free-free emission from the same material seen at higher frequencies by a factor of just over 2. This calls into doubt the interpretation, because the higher coronal temperature makes it more likely that free-free emission will be optically thin, and also more likely that gyroresonance emission will be optically thick. We note that the highest degrees of circular polarization are generally seen at the edges of 1.5 GHz active region sources (Dulk & Gary 1983; Gopalswamy et al. 1991), and these might be due to the gyroresonance component rather than the free-free component as usually assumed.

7. ACTIVE REGION EVOLUTION

The evolution of the active region as seen in Figure 1 is the combination of two effects: the actual temporal evolution of the corona above the active region which changes its radio emission; and the change in the aspect angle with which we view the region. It is obvious that for a region at the limb, foreshortening will play an important role in the appearance of the region. However, again there are two effects: one is that the angle between the line of sight and magnetic field lines is different from what it would be for a disk region; and also any optically thick emission obscures the features of trailing sources. As we have seen in the preceding section, gyroemission will always select against magnetic field lines parallel to the line of sight, particularly in the o-mode. Thus at the limb most of the emission should be associated with vertical field lines, whereas near disk center the opacity comes mainly from horizontal fields.

Table 3 shows how the observed flux from the active region at 5 GHz varied with time. We believe that the steady increase from September 11 to September 13 is mostly due to the effect of foreshortening at the limb. The drop in the R and V fluxes from September 13 to September 17 is due to the fact that the polarized flux from the trailing part of the active region changed from right-handed to left-handed between the two observations. The peak brightness temperature in both R and L maps of the region increased by over $3 \times 10^5$ K from September 13 to September 17, even though the overall complexity of the region decreased as the trailing spot disappeared, but
we have no way of determining whether the increase in brightness temperature was due to line-of-sight effects or to evolution of the region (which became magnetically simpler in the photosphere, as discussed in § 3).

The important aspects of evolution revealed by Figure 1 are the following.

1. On at least three consecutive days the polarization of the trailing region was inverted with respect to the photospheric field.

2. For the limb sources a region of negative polarity appeared at the leading edge of the active region source.

3. As the active region evolved the trailing source, initially brighter than the morphologically simpler leading spot, weakens. However, the disappearance of the spot does not lead to a disappearance of emission at that location: instead, the peak temperature drops from $1.3 \times 10^6$ K on September 13 to $7.5 \times 10^5$ K, i.e., it remains quite intense. We interpret this as due to the continuing presence of 600 G fields in the corona over the trailing region, despite the disappearance of the intense photospheric sunspot fields, while allow nearly optically thick gyroresonance emission at coronal brightness temperatures.

4. The 5 GHz peak, when seen close to disk center, is clearly not over the sunspot. This complicates attempts to deduce the height of 5 GHz sources except for limb regions, and in this case even the limb region (September 11) did not show any shift from which one could deduce the projected height.

5. The distance between the two radio peaks on September 12 and 13 was less than the separation of the underlying sunspots. The apparent difference in separations increased as the region rotated onto the disk, consistent with a picture in which both radio sources were displaced toward the center of the active region, relative to the sunspots. The leading radio source in particular appears to be well behind the leading sunspot.

Thus we believe it unlikely that these can be regarded as unresolved ring sources, but rather indicate a genuine asymmetry which is to be expected: fields between the two sunspots will be greater than elsewhere around the active region. Temperature and density asymmetries may also play a role, but we believe that they are less likely explanations: thus, the observed temperature is a typical coronal temperature and a temperature explanation of the asymmetry would require that the other parts of the active region be rather cool; and density can only play a role if it makes the gyro-emission optically thin, which requires $n \lambda B \ll 10^{16}$ cm$^{-2}$. The latter condition is unlikely to be satisfied over a large volume of the corona above the active region.

## TABLE 3

<table>
<thead>
<tr>
<th>Date</th>
<th>$R$ Flux (sfu)</th>
<th>$L$ Flux (sfu)</th>
<th>$I$ Flux (sfu)</th>
<th>$V$ Flux (sfu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 11</td>
<td>2.48</td>
<td>1.60</td>
<td>2.04</td>
<td>+0.44</td>
</tr>
<tr>
<td>Sep 12</td>
<td>4.06</td>
<td>2.66</td>
<td>3.36</td>
<td>+0.70</td>
</tr>
<tr>
<td>Sep 13</td>
<td>5.01</td>
<td>3.05</td>
<td>4.03</td>
<td>+1.01</td>
</tr>
<tr>
<td>Sep 17</td>
<td>4.22</td>
<td>3.43</td>
<td>3.83</td>
<td>+0.40</td>
</tr>
</tbody>
</table>

8. DISCUSSION

8.1. The Location of Intensity Peaks in Active Regions

Figure 2 shows clearly that the peak emission at a given frequency moves eastward from the umbra as one decreases frequency (increases height) from 15 to 8.3 to 5 GHz. We are confident that in each case the peak is due to optically thick gyroresonance emission, and thus it outlines a specific magnetic field: for the x-mode this is 1800, 1000, and 600 G at 15, 8.3, and 5 GHz respectively. Further, the two lower frequencies are well away from the sunspot. The 5 GHz source is close to, but not quite over, the photospheric neutral line in the active region.

Before high-resolution images of active regions were available, theoretical arguments predicted that the peaks in such images should lie over a sunspot umbra. The argument is as follows: since temperature is generally thought to increase with height in the corona above active regions, the peak temperature should arise in the highest optically thick gyroresonant source. This should lie over the umbra because magnetic fields in the corona are thought to be strongest there, and thus the gyroresonant layers are at their greatest height at a given frequency.

The numerous observations of active regions with WSRT and the VLA in the last 10 yr (Kundu & Alissandrakis 1975; Kundu et al. 1977; Felli, Poletto, & Tofani 1977; Lang & Wilson 1979; Alissandrakis et al. 1980; Felli, Lang, & Willson 1981; Schmahl et al. 1982; Lang et al. 1982; Chiuderi-Drago et al. 1982; Alissandrakis & Kundu 1982; Lang & Willson 1982; McConnell & Kundu 1983; Lang, Willson and Gaizausauskas 1983; Shibasaki et al. 1983; Dulk & Guy 1983; McConnell & Kundu 1984; Shevgaonkar & Kundu 1984; Alissandrakis & Kundu 1984; Strong, Alissandrakis, & Kundu 1984; Kundu & Alissandrakis 1984; Schmahl et al. 1984; Shevgaonkar & Kundu 1985; Willson 1985; Kundu & Shevgaonkar 1985; Akhmedov et al. 1986; Willson & Lang 1986; Webb et al. 1987; Lang et al. 1987a, b; Gary & Huford 1987; Willson & Lang 1987; Shevgaonkar & Kundu 1989; Nitta et al. 1991) have confirmed that there are sources above sunspots which have coronal temperatures. When spatial resolution is adequate, these sources are usually found over the penumbra and not the umbra. However, it is rare for the peak in an active region to be above a sunspot; instead, the peaks generally seem to lie over the photospheric neutral line (e.g., Kundu et al. 1977). But this presents a problem of interpretation, since the neutral line is often a long distance from any strong photospheric fields, and based on extrapolations of surface fields one often does not expect fields in the corona there strong enough (600 G at the most often observed frequency of 5 GHz) to produce optically thick gyroresonance emission. The observations of Gaizauskas & Tapping (1988) are also consistent with this: they studied the location of compact 2.8 cm sources relative to optical features in a large number of active regions, using relatively low spatial resolution observations with a single-dish telescope. They found a poor association between the brightest 2.8 cm features and sunspots, but good associations with plage and neutral lines.

We argued previously on the basis of the 15 GHz data alone that magnetic fields emerging from the sunspot appeared to be
confined to a small flux tube in which they were exceptionally strong (WKG). The shift of the location of the brightness temperature peak with decreasing frequency is further evidence for this. We will compare the magnetic field strengths predicted by extrapolations of photospheric magnetic fields with the strengths revealed by these observations elsewhere; here we speculate that the field over neutral lines is quite strong due to powerful currents associated with the corona there, and that active region peaks tend to occur there because (1) there is adequate magnetic field strength for gyroresonance emission to be optically thick; (2) the magnetic fields tend to be horizontal there, and thus orthogonal to the line of sight for regions not far from disk center (which increases opacity; see eq. [3]); and (3) the heating associated with this part of active regions may be more vigorous than coronal heating over sunspots, so that plasma temperatures tend to be higher near the neutral line. The effect of the angle \( \theta \), which gives large opacity over the neutral line for a region on the disk due to the fact the field lines are horizontal and therefore orthogonal to the line of sight (Kundu & Alissandrakis 1984), can only play a role if the magnetic fields are already strong enough over the neutral line. We do not invoke a common explanation for high temperatures over the neutral line, namely loop models which show that the temperature should be greatest at the tops of stable loops (Rosner, Tucker, & Vaiana 1978), since we require strong magnetic fields to explain our neutral line sources and fields are generally thought to be weak at loop tops.

However, in these observations the neutral line sources cannot only be due to currents in the vicinity of the neutral line. If currents are low except over the neutral line, then all the high magnetic fields away from the umbra will be coincident at the neutral line, which is not the case in this observation (i.e., the 5 and 8.3 GHz peaks are at different locations). In cases such as the observations of Kundu & Alissandrakis (1984), where the active region peaks at 5 GHz occur in a ridge running parallel to the photospheric neutral line, the currents may be large only in the vicinity of the neutral line, whereas in this observation the peaks at different frequencies, and the overall structure of the radio emission, outline a ridge running perpendicular to the neutral line (seen best in the 15 GHz L map).

8.2. "Spot Source" Size Scaling

Table 2 indicates how the area \( A \) of the source which we associate with gyroemission scales with frequency. We have plotted the variation in Figure 9, which shows that the variation from 5 to 15 GHz in \( R \) appears remarkably linear on a log-linear plot (the size of the \( I \) source is clearly dependent on that of the \( R \) source, particularly where there is no \( L \) source). This leads to the approximate law

\[
A \propto 2.4^X
\]

for which we cannot presently find any physical basis. The simplest scaling relating size to wavelength comes from the magnetic flux conservation law, \( A \propto B^{-2/3} \) together with the assumption that the frequency is proportional to magnetic field for gyroemission at a fixed harmonic, and ignoring projection effects. However, this would imply that the area is proportional to wavelength (assuming that the same harmonic is seen at all wavelengths), and Figure 9 shows that the area is a much steeper function of wavelength than this. An alternative scaling based on the dipole field approximation would give \( A \propto B^{-2/3} \propto \lambda^{2/3} \) which is an even weaker dependence on wavelength. The Owens Valley frequency-agile interferometer has also been used to estimate the dependence of source size on frequency. Hurford (1986) finds a power-law dependence \( A \propto \lambda^n \); however, the technique he uses apparently does not distinguish between the spot gyroresonance source and the halo component, and so his measurement is not strictly comparable with ours.

8.3. Gyroresonance Emission in the o-Mode: Second or Third Harmonic?

Based on calculation rather than observation, numerous authors have shown that it is likely that the highest o-mode gyroharmonic optically thick in the corona is the second, while the x-mode is optically thick at the third gyroharmonic. It follows that the two modes should present radiation from different magnetic field layers. The entries in Table 2 can be used to check the plausibility of this model. It clearly does not apply to this sunspot: thus the o-mode at 8.3 GHz from the 1500 G layer and the x-mode at 15 GHz from the 1800 G layer should be of similar size, as should the o-mode at 5 GHz from the 870 G layer and the x-mode at 8.3 GHz from the 1000 G layer. This is clearly not the case: the size of the o-mode source is in both cases more comparable with (albeit slightly smaller than) the size of the x-mode source at the same frequency than with that at the next highest frequency. Since, as we noted above, the o-mode opacity is much smaller than the x-mode opacity except near \( \theta = 90^\circ \), we must conclude that the fields are nearly horizontal in much of the source.

The possible effects of beam size must be taken into account. We have assumed that the outer boundaries of the x- and o-mode sources are identical, as discussed above, so that even if...
an unresolved hole is present in the center of the radio source the deduced size of the outer boundary should be the same for $o$- and $x$-mode sources in the same magnetic field layer. The brightness temperature of the $o$-mode source will be diluted more than that of the $x$-mode source by the fact that the central hole is larger but still unresolved, but that does not affect conclusions based on the dimension of the outer boundary of the gyroresonance source. Incidentally, this dilution of the brightness temperature might be responsible for the difference between the peak $R$ and $L$ brightness temperatures on September 17.

8.4. Mode Coupling at the Limb

We observed apparent mode coupling from the active region at 5 GHz on September 11, 12, and 13. The conventional explanation for mode coupling is the following (Cohen 1960; Melrose 1980; Bandiera 1982): somewhere along the line of sight to the source of emission in the trailing part of the active region on the east limb the ray must encounter a point where the magnetic field is perpendicular to the line of sight (called the “$QT$” point), and hence where the polarization of the $x$-mode flips from say, $L$ to $R$. Mode coupling at this point determines the emerging polarization of the emission, which we assume to be initially $x$-mode from the trailing region and therefore $L$: if coupling is strong the radiation will remain left-circularly polarized and thus must couple to the $o$-mode; if coupling is weak then the radiation remains $x$-mode and emerges as $R$ polarization. Coupling is strong if $Q > 1$, where

$$Q = \left( \frac{f_0}{f'} \right)^4, \quad f_0^2 = \frac{\pi f_p f_B}{2 c (\partial \theta / \partial l)}, \quad (7)$$

and here $\theta$ is the angle between the magnetic field and the line of sight. Within an active region we adopt the values $B = 100 G, n = 10^9 cm^{-3}$, and $\partial \theta / \partial l = \pi / 10^9 cm$; then $f_p = 13 GHz$, and we expect that radiation at 5 GHz encountering a $QT$ point inside an active region will show polarization reversal as observed.

However the fact that no reversal is seen at 1.5 GHz (Gopalswamy et al. 1991) seems to contradict the above result, which says that reversal should be observed at all frequencies below $f_p$. We discuss this point in some detail in White et al. (1991b), and show that in fact we expect that $f_p$ will be much smaller for a line of sight to the 1.5 GHz source than it will for the 5 GHz source. This is because the magnetic field in the $QT$ layer largely determines the critical frequency; in the $QT$ layer for the line of sight at 1.5 GHz, we expect this field to be weaker than it is in the 1.5 GHz source itself, which is about 50 G, compared with 600 G in the 5 GHz source. Thus if we put $B = 10 G, n = 10^8 cm^{-3}$, and $\partial \theta / \partial l = \pi / 10^8 cm$ for the $QT$ region at 1.5 GHz, then $f_p = 1.3 GHz$, and we do not expect to see polarization inversion. Thus the picture in which 1.5 GHz emission is optically thick thermal emission high in the corona while 5 GHz emission is thermal gyroresonance emission from much lower is consistent with the observations of polarization at the two frequencies.

The only peculiar feature of the polarization observations is the presence of $L$ polarity at 5 GHz preceding the active region on September 11. This feature is statistically highly significant.

We can attribute it to the presence of magnetic field lines from the spot closing in the photosphere in the low-field region in front of the spot, producing magnetic field directed away from us in this source region so that the $x$-mode polarity is $L$ there; or alternatively there may be a mode-coupling region in front of that location which inverts the polarization of the originally $x$-mode radiation. A similar but much weaker feature is seen on September 12.

9. CONCLUSIONS

We have presented high dynamic range radio observations of a solar active region at a number of frequencies and on a number of days. The higher dynamic range removes much of the uncertainty often associated with the analysis of radio observations of such large structures due to flux on large scales which is missing from the data, and uncertainty about the reality of features (e.g., see the discussion by Bastian 1989). In particular, the multifrequency observations allow us to identify unambiguously the contributions of free-free and gyroresonance emission in the active region. The different spectra of these emission mechanisms are evident simply in comparing 5, 8.4, and 15 GHz images, and by using the 15 GHz $L$ data as a measure of the free-free contribution, we can do careful numerical analysis, allowing us to plot the spectrum of each component of the active region emission.

An overall picture of the different components to the active region emission as a function of frequency is clear from these observations. We see no evidence which requires nonthermal emission at any frequency above 1 GHz (the noise storm emission at 333 MHz is nonthermal). The data are consistent with optically thick free-free emission dominating at 1.5 GHz but with a component from gyroresonance emission at the edges of the source, optically thick gyroresonance emission dominating at 5 and 8 GHz, and an optically thin flat-spectrum free-free component that is present at 5 GHz and dominates at higher frequencies. The data are adequate to even identify the role of optically thin gyroresonance emission at 5 GHz. The brightness temperature of the optically thick gyroresonance component is roughly constant up to nearly 15 GHz. Thus the contribution of the gyroresonance source to the active region flux is most dependent on the size of the gyroresonance source. It has been found previously that the active region flux drops rapidly with increasing frequency: Hurford (1986) used frequency-agile interferometer data to measure the brightness temperature and source size of a sunspot source. He found that below 10 GHz the brightness temperature did not change greatly while the source size decreased as frequency increased; above 10 GHz the source size was constant, but the brightness temperature decreased sharply with frequency. In his case, if we interpret 10 GHz as the highest frequency at which optically thick gyroresonance emission contributes, then his observations of a steady drop in source size up to that frequency are entirely consistent with the results here, where an exponential dependence of source size with magnetic field strength (assumed to be inversely proportional to wavelength) played the dominant role in the drop of flux with increasing frequency, not a decrease in brightness temperature.

It is of interest that the main radio diagnostic of solar activity, the 10.7 cm flux, originates in a frequency range where
there must be a transition from optically thick free-free emission, seen at 1.5 GHz, to optically thick gyrosesonance emission, seen at 5 GHz. This has been noted by many authors previously (e.g., see Tapping & DeTracey 1990; Oster 1990; and references therein). In the picture we presented above this occurs by having optically thick free-free emission over the densest part of the corona above the active region, with an area of gyrosesonance emission approximately surrounding it at the edges. As frequency increases, the size of both optically thick free-free and gyrosesonance sources decrease, but at a high enough frequency eventually the optically thick free-free source disappears, leaving just the gyrosesonance source.

One striking result of these observations is that they are clearly inconsistent with the usual assumption that x-mode gyrosesonance emission comes from the third harmonic but that o-mode is second harmonic, since we find that the size of the x- and o-mode sources is about the same at any given frequency and of different magnetic field strengths in the corona. The 15 GHz R source indicates the small area in which 1800 G fields occur. The compact 8.4 GHz source indicates the extent of 1000 G fields; the compact 5 GHz sources indicate 600 G fields; the excess emission in the ridge at 5 GHz indicates 450 G fields; and the excess flux at 1.5 GHz is interpreted as due to 130 G fields at the edge of an optically thick free-free source. The bipolar noise storm appears to outline a magnetic flux tube on a very large scale, with the leading leg of the tube well in front of the active region. We plan a comparison of these results with extrapolations of photospheric vector magnetograph data in a future paper.

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