Strong magnetic fields in the solar corona

S. M. White, M. R. Kundu and N. Gopalswamy

Astronomy Program, University of Maryland

Abstract. *We show that fields of 1800 gauss can exist in the corona based on observations of gyroresonance emission at 15 GHz at coronal temperatures. The strong fields occur in a small source radiating in the extraordinary (x) mode over the penumbra of a large symmetric sunspot. The optically-thin ordinary (o) mode emission from the region shows a nearby peak at only 36000 K which may be due to a sunspot plume, and a hole over the umbra consistent with the expected low-density material there. The x mode source is highly asymmetric, despite the apparent symmetry of the sunspot, and its appearance and location imply that the strongest magnetic fields in the corona are localized in a compact flux tube.*

1 Introduction

The maximum strength of the magnetic field in the corona is an important but largely unknown parameter in studies of solar activity. Magnetic fields in the solar photosphere have been measured for many years with optical magnetographs based on the Zeeman effect. Field strengths of up to 4000 gauss are found in the umbrae of sunspots. However, due to the large drop in pressure through the transition region, flux tubes emerging from the photosphere expand rapidly, with a corresponding sharp decrease in the magnetic field strength above the chromosphere. Observations of the Zeeman effect are also possible for ultraviolet lines formed in the transition region, and this technique has demonstrated that fields of 1000 gauss tend to be common there, with a maximum reported field of 1600±1100 gauss (Henze et al. 1982). However, Zeeman splitting of lines in the corona is not presently observable.

The simplest direct measurement of magnetic fields in the corona is the detection of gyroresonance emission at microwave wavelengths (e.g. Ginzburg and Zheleznyakov 1961). Such emission occurs at discrete harmonics of the gyrofrequency, $f_B = 2.8\ B_{gauss}$ MHz. The harmonic can be identified from knowledge of typical coronal densities and the observed temperature together with the appropriate emission formula. It is generally accepted that for usual conditions the highest optically thick harmonic in the x mode is the third, and in the o mode the second. The maximum field in the corona can be estimated from the spectrum of the active region emission, since the difference between the flat spectrum of thermal bremsstrahlung and the steep spectrum of typical gyroresonance emission allows one to estimate the maximum frequency at which gyroresonance by coronal material contributes, provided the spectra are simple and the observations are at closely spaced frequencies. Gary and Hurford (1987) report one such observation with the Owens Valley frequency-agile interferometer in which a maximum coronal field of 1400 gauss was found, and Akhmedov et al. (1986) report one-dimensional observations with the Ratan 600 telescope in which a field strength of 1700 gauss at the bottom of the corona was estimated.

However, these observations are presently limited by lack of full imaging capability. One then has only restricted information on the distribution of coronal fields with respect to the underlying photospheric fields. With the Westerbork Synthesis Radio Telescope (WSRT) and the Very Large Array (VLA) one can make high-resolution images of solar active regions which allow the relative location of coronal and photospheric features to be determined. The disadvantage of such observations is that only a small number of frequencies is available, and thus only the corresponding discrete values of magnetic field strength can be observed. Most previous observations of gyroresonance emission have been carried out at 5 GHz, which corresponds to a field of only 600 gauss (x mode).

Here we present the first clear VLA detection of gyroresonance emission at coronal temperatures at 15 GHz, implying that field strengths in the corona can exceed 1800 gauss. This observation is remarkable in that the strongest coronal fields detected by the VLA apparently do not lie over the strongest photospheric fields.

2 Observations and Analysis

On 1988 September 17 we observed AR5148, the target active region for the SMM/International Solar Month campaign at that time, during 10 hours with the VLA. AR5148 and another region were observed at .33/1.5, 5.0, 8.3 and 15 GHz sequentially, so that the total integration time for the 15 GHz observations discussed here is less than an hour. However, due to the spacing of the observations at 15 GHz the u,v coverage was excellent. The region was close to disk center (S10W07). The VLA was in its most compact ("D") configuration, which is excellent for observing extended structure. However, at 15 GHz, the VLA is nominally insensitive to structures larger than about 90" (i.e., cannot recover their full flux), and this effect is seen in our maps. For the left-circular-polarization (L) map the maximum entropy method (MEM), which is suited to the task of mapping extended emission, was used to make maps which show more extended emission. We have used video magnetograms and

off-band Hα images provided by the Big Bear Solar Observatory (BBSO; courtesy of Dr. Alan Patterson) for accurate overlays on the radio data.

3 Radio emission from the active region at 15 GHz

On Sep 17 AR5148 is dominated by a large leading spot with a circular umbra and penumbra. In the off-band Hα images the spot is apparently symmetrical with a fairly uniform penumbra of about 40 arcsec diameter. The videomagnetograms indicate that it is of positive polarity, but with magnetic field gradients which are strongest towards the leading edge of the umbra. The peak field is listed in *Solar Geophysical Data* at 2300-2800 gauss. There are a number of small weak pores with no visible penumbra in the trailing part of the active region; the neutral line lies just east of the penumbra and runs roughly north-south.

Figure 1 presents the R and L maps at 15 GHz. For comparison with the optical data we have overlaid the L map on the off-band Hα image and the R map on the videomagnetogram. The R map shows a compact source over the penumbra of the sunspot, with a nominal peak brightness temperature of 6.8×10^5 K. The map shows artefacts characteristic of amplitude errors: negative lobes close to the peak which reach about 10% of the peak value (the map rms elsewhere is only 2200 K, or 0.3% of the peak flux). There are no corresponding lobes in the dirty beam which can explain these artefacts. While the self-calibration procedure was used to improve the R map, it was unable to remove these lobes. The most likely cause of this artefact is time variability. When maps of individual scans are made (12 scans each of about 4 minutes duration, separated by about 40 minutes), we find that the map peak value does not greatly vary from scan to scan (typically 10% variation). On the other hand the location of the peak does vary, typically by half a beam-width or more, from scan to scan. This could easily be the source of the artefacts in the map made from all data combined. Since the scan maps themselves also show the negative lobes, any variability present seems to take place on a timescale shorter than 4 minutes.

These negative lobes complicate the analysis of the peak properties, since they can influence fits of a gaussian beam shape to the source. However a fit gives a peak brightness temperature of 7.3×10^5 K with a source size of 6.3"×5.0", implying that the source is larger than the clean beam in this map (4.5"×4.0"). If this size is actually due to motion of the source "smearing out" its flux, then the true brightness temperature will be higher. The total flux in this compact source is about 0.49 sfu. The map shown was actually made only with visibilities from the longer baselines, in order to try to improve the noise characteristics, and thus it cannot show any extended emission.

The L map shows no peaks more intense than 36000 K (map rms is only 600 K), which is a factor of 20 weaker than in the R map. Note that a quiet-Sun temperature (about 10000 K) should be added to the values measured in the VLA maps to adjust to true brightness temperatures. The active region shows up as an extended source which is mostly at a brightness temperature in excess of 5000 K, but is surrounded by a weak negative basin at –2000 to –3000 K (not shown: they occupy the outer regions of Fig. 1b which are devoid of contours). This negative basin indicates that the active region source was actually larger than the VLA's baselines could image, i.e. significant emission falls into the negative sidelobes of even the shortest baselines available. However, by comparison with the active region flux at longer wavelengths we can estimate that at most about 30% of the 15 GHz L flux is missing, and when this flux is distributed over the large area of the optical active region it only changes the background level by a small amount. Thus we are confident that none of the relevant structures in the L maps are artefacts. A ridge of emission which is brighter than 12000 K curves eastward from the spot and contains within it several peaks, the brightest of which reaches 33000 K. These peaks do not appear to be associated with any of the pores trailing the spot. The brightest peak in the L map is not in this ridge but at the edge of the sunspot umbra, overlapping and nearly coincident with the strong peak in the R map. However, careful fits to the map peaks indicate that this L peak is offset from the R peak by 4.0"±0.2", in the direction directly towards the umbra. Thus the R peak is more than 95% polarized. With respect to the orientation of the underlying photospheric fields the polarization corresponds to the x mode, consistent with gyroresonance theory.

A very interesting feature of the L map is the "hole" which appears just to the south-west of the peak. Note that the rim of the hole, which includes the brightest source in the map, is roughly circular and of the same dimension as the penumbra. There are several "valleys" in this rim. We believe that the hole should lie over the umbra for two reasons: it indicates low density material, and observations at all wavelengths show the lowest active-region densities over umbrae; and the rim of the hole is then coincident with the penumbra. The brightness temperature drops from about 5000 K in the surrounding rim to 1500 K in the hole (or, if we add the background to the map values, from 15000 K in the rim to 11500 K in the hole). Note that if we translate the maps so that the peak in the R map lies over the strongest magnetic fields, the hole then lies well in front of the umbra, on the outer edge of the penumbra.

4 Discussion

(i) Emission mechanisms

The peak in the R map is too strong to be free-free emission from plausible coronal densities, and hence must be due to gyroresonance opacity. The peak brightness temperatures in the L map are too high to be chromospheric, and we assume that most of the emission is due to optically-thin thermal bremsstrahlung from overlying coronal material. Previous 15 GHz observations have often seen high polarization, but without simultaneous high brightness temperatures over active regions (Chiuderi-Drago et al. 1982; Lang, Willson and Gaizauskas 1983; Shevgaonkar and Kundu 1984; Willson and Lang 1986) .

(ii) Coronal parameters

With images of the region in two different emission mechanisms we can tightly constrain the coronal parameters in the sources. From the L map we can analyze conditions averaged through the whole corona, weighted by the opacity formula for thermal bremsstrahlung which preferentially selects cool, dense material. Using the observed coronal brightness temperatures of about 1.5×10^6 K and an appropriate scale height we can deduce densities for the coronal material using standard free-free formulae (e.g. Dulk 1985). For the compact peaks at 30000 K we adopt a line-of-sight depth of 5000 km, consistent with their size, and this requires a density of 9.0×10^9 cm^{-3}. For the long ridge at a brightness temperature of about 15000 K we adopt a greater source thickness of 10000 km, and this requires a density of 4.5×10^9 cm^{-3}. These values are plausible for active region loops low in the corona.

We can check the parameters for the x mode gyroresonance source using the formula for the opacity of the resonant layer, which assumes that the magnetic field varies linearly with height along the line of sight with a scale length $L_B = B/\left|\frac{\partial B}{\partial l}\right|$. If we assume that the emission is optically thick at T = 7.3×10^5 K, then the resulting density would produce a free-free feature in the L map which is brighter than anything observed (of order 1.5×10^5 K). Thus we assume that the true temperature in the source is coronal, and that the optical depth is 0.693. If we adopt the values $\theta = 37°$ (θ is the angle between the magnetic field direction and the line of sight, and we require $\cos\theta > 0.79$ in order to limit the o-mode gyroresonance contribution below 10000 K as observed), T = 1.5×10^6 K, L_B = 10000 km and harmonic number s = 3, then the observed brightness temperature requires a density of 9.0×10^8 cm^{-3} (this is inversely proportional to the assumed value of L_B). We note that with the same parameters optically-thin gyroresonance emission at the fourth harmonic would require a density of 10^{11} cm^{-3}, which is well in excess of the accepted range of densities in the corona, and which can in any case be ruled out because it would again produce a much stronger feature in the L map. We also note that the angle θ cannot be made too small without requiring excessive densities. For example, $\theta = 20°$ would require a coronal density of 7.7×10^9 cm^{-3} and again produce a large signature in the L map.

The coronal density over the hole in the L map is less than 10^9 cm^{-3}, and thus we believe that the peak in the L map over the spot is not coronal (if so, there is a density jump of a factor of 10 over a very short distance). We assume instead that it is a sunspot plume (Foukal et al. 1974) . With a typical plume temperature of 2×10^5 K (Noyes et al. 1985) and with a brightness temperature of 35000 K and a scale length of 3000 km along the line of sight we require a density of 7.5×10^9 cm^{-3}, which is again plausible for sunspot plumes. We note that since free-free emission also favors the x mode in strong fields, we should expect to see emission in the R map at several times the value found in the L map. This is the case: at the position of the L peak, the R brightness temperature is 1.8×10^5 K. The R source falls off very rapidly, however, and at the south-western edge of the L source the R brightness temperature is too low to be consistent with the L values. However, due to the presence of the negative lobes at the edge of the R source we cannot be confident of the true R brightness temperature at this location.

(iii) Inhomogeneity in the corona above the sunspot

Due to the $n^2T^{-0.5}$ dependence of the brightness temperature in free-free emission, inhomogeneities in the L map must be due to density structure. The ridge of emission extending eastwards of the spot presumably represents dense active region loops: peaks in the ridge must be density peaks, and from the analysis above the density varies by a factor of 2 over short distances. We should emphasize that the "rim" structure in the L map is also due to density contrast and thus has an interpretation different from the "ring" structure produced by gyroresonance emission in a dipole field configuration (e.g., Gelfreikh and Lubyshev 1979). However we speculate that some ring structures previously identified as gyroresonance rings may in fact be density depressions (cool material may also play a role, e.g., Alissandrakis and Kundu 1982).

The interpretation of the inhomogeneity represented by the R gyroresonance source is more difficult. In a simple dipole model the 1800 gauss surface in the corona above the sunspot would be azimuthally symmetric, i.e., with a symmetric atmosphere there should be a ring of optically thick emission observed (there are sufficient short baselines to easily see a ring structure of up to 90" diameter). Such a ring is not observed: is this due to temperature, density or magnetic field inhomogeneity? A density structure seems to be inconsistent with the maps: it would need a very low density in the rest of the ring which is incompatible with the L map. If instead density is constant around the 1800 gauss surface and temperature varies, we deduce a steep temperature gradient. Effectively this implies that the corona dips in height right at the point where the peak occurs. Finally, if the 1800 gauss magnetic field is actually concentrated in a compact flux tube rather than being distributed symmetrically around the sunspot umbra, then this flux tube will be the only place where the 1800 gauss surface intersects the corona. Such a concentration of field could explain the unusual detection of 1800 gauss fields in the corona. The o-mode peak close to the gyroresonance source may then represent sunspot plume material lower in the the same flux tube.

5 Conclusion

We have shown that magnetic fields of at least 1800 gauss can exist in the solar corona. In fact, since the flux from the gyroresonance source is still a significant fraction of the total flux from the active region at 15 GHz, we note that the maximum value of the field in the corona is probably higher than 1800 gauss. High magnetic field strengths in the corona permit high energy densities to be stored there which can be released in solar flares. We also find that there is a severe inhomogeneity in the corona above the sunspot. This must be due either to a very sharp temperature discontinuity, or to the concentration of magnetic flux from the sunspot in a compact flux tube. Strong density gradients are also seen in the free-free emission, and in particular the low density of material in the corona directly above the sunspot is seen.

The relationship between the R peak and the L peak remains unclear. The picture we favor is that both are from a loop originating in the spot and curving up and to the left, towards the trailing part of the active region where the longitudinal magnetic field polarity is reversed. The L source arises in low, cool dense material at the base of the tube, and in projection is therefore offset towards the umbra from the R source which lies at the less-dense coronal heights. We speculate that the loop might be identified as a sunspot plume in UV observations, and the apparent variability in the source seen in the R map may be related to the motion of material seen in plumes by Nicholas et al. (1982).

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Figure Captions

Figure 1. Overlays of the 15 GHz maps of AR5148: (a) right circular polarization overlaid on the BBSO videomagnetogram, and (b) left circular polarization superimposed on the off-band Hα image. 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 "grey" (low-field) region, which is white in the case of positive polarity (line-of-sight field towards us) and dark for negative polarity. The contours in the R map are at -4, 4, 8, 12, 16, 24, 32, 40, 48, and 64×10^4 K. The contours in the L map are at 1, 2, 3, 4, 6, 8, 10, 12, 16, 20, 24, 28 and 32×10^3 K. No negative contours are shown in the L map for clarity: the region of positive flux in the map is surrounded by a weak negative "basin". Note that the contours over the sunspot umbra are decreasing (the depressed contours are not marked in order to retain visibility of the grey-scale features).

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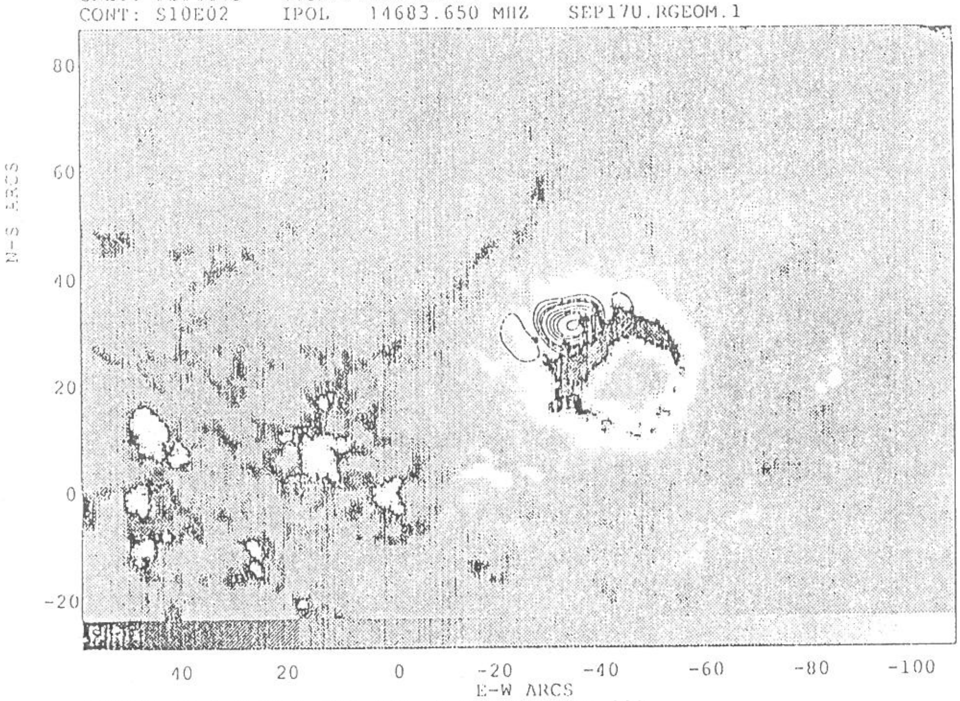

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PEAK CONTOUR FLUX = 6.7998e+05
LEVS = 4.0000e+04 * (-1.00, 1.000, 2.000,
3.000, 4.000, 6.000, 8.000, 10.00, 12.00,
16.00, 20.00, 24.00, 28.00, 32.00, 36.00)

Fig. 1a

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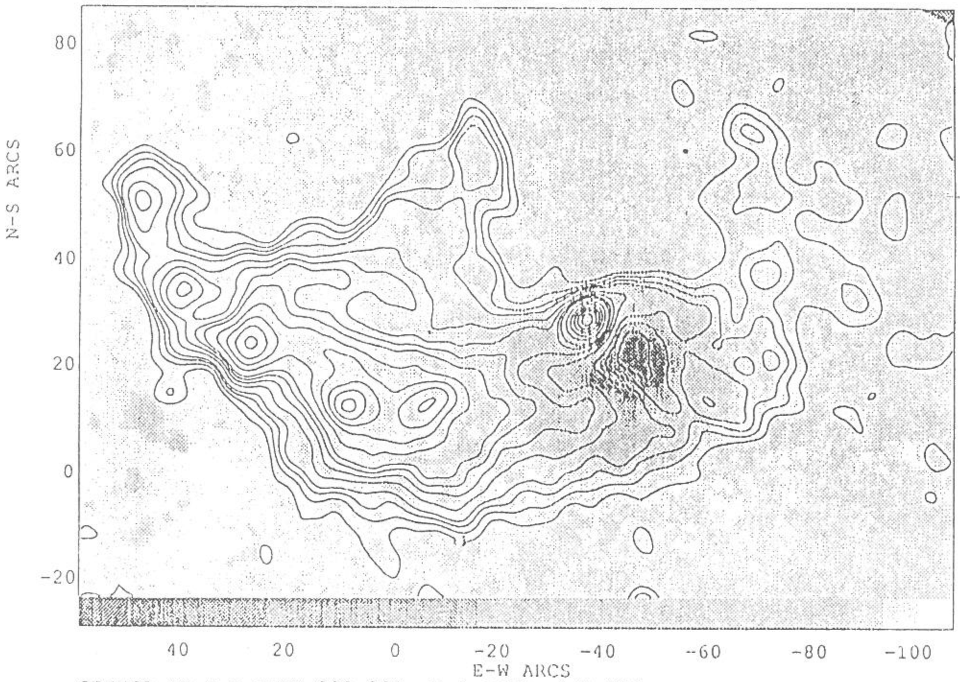

CENTER AT E-W ARCS 220.000 N-S ARCS -247.000
GREY SCALE FLUX RANGE= 6.0000e+01 2.2000e+02
PEAK CONTOUR FLUX = 3.4866e+04
LEVS = 1.0000e+03 * (1.000, 2.000, 3.000,
4.000, 6.000, 8.000, 10.00, 12.00, 16.00,
20.00, 24.00, 28.00, 32.00, 36.00)

Fig. 1b