

Magnetic Sensitivity of Radio Emission

There are three main radio emission mechanisms that operate in the Sun. In order of their usefulness for direct measurement of coronal magnetic fields, the broad families are *gyroemission*, *free-free emission*, and *plasma emission*. Gyroemission can be further subdivided into a several types depending on emitting particle energy, while plasma emission comes in a large variety of sub-types.

The single most useful mechanism for direct measurement of coronal magnetic fields is a type of gyroemission called *gyroresonance* emission, which is a resonant emission process at frequencies f that are low harmonics s of the cyclotron frequency, $f_B = eB/2\pi mc \approx 2.8 \times 10^6 B \text{ Hz}$. This process is relevant for thermal plasma in the solar atmosphere. Thus, for the coronal conditions above active regions, the frequencies produced by electrons in a region with magnetic field strength B are $f = sf_B \approx 2.8 \times 10^6 sB \text{ Hz}$

Although this is the most useful mechanism for measuring magnetic fields in *coronal magnetography*, it is generally limited to relatively strong-field regions in active regions. We emphasize that the other radio emission mechanisms are also sensitive to magnetic field strength and direction, and can be exploited to give information on the magnetic field as well. Some of these mechanisms will be useful in weak-field regions. This document will concentrate on the use of gyroresonance emission for coronal magnetography, although at the end we mention how the other types of emission may be used.

A remark before proceeding: The coronal magnetic field is inherently 3D, and therefore its measurement is a very different problem from photospheric measurements. The photosphere provides a well-defined surface that has no analog in the corona. We focus below on a technique for measuring the magnetic field at the base of the corona, which is the closest thing to a 2D “surface” that exists. This is a first step toward more sophisticated techniques to model the entire 3D corona, in which FASR observations will be combined with high-resolution observations from the optical to the EUV.

Coronal Magnetography in Active Regions

Background Issues

In this section, we briefly discuss some of the details that are relevant to use of gyroresonance emission for coronal magnetography. This subsection can be skipped if only the practical aspects of the technique are desired.

Consider a typical active region whose magnetic field strength is greatest above sunspots, and decreases with distance away from these sunspots. Although a given parcel of coronal plasma emits simultaneously at many frequencies $f = sf_B$, generally only one of these frequencies (one harmonic) is important. This is the *highest optically thick harmonic*, and for typical coronal parameters it will be the 2nd, 3rd, or 4th harmonic. Since only one frequency is important at any one location in the corona, let us now consider observations at a given frequency along a given line of sight. Somewhere along this line of sight, starting at Earth and progressing inward toward the solar surface, we will come to a point where we reach the highest optically thick harmonic. Which harmonic it is depends on temperature, density, and magnetic field direction, but not on magnetic field strength. Where in the corona it is depends *only* on magnetic field strength, not on these other parameters.

Thus, the problem of measuring coronal magnetic fields becomes one of determining *which* harmonic is the highest optically thick one along a given line of sight—so we must now consider the issue of optical depth, or opacity. The review of White and Kundu (1997) gives an excellent discussion of gyroresonant opacity, which is encapsulated in Figure 1, reproduced from their paper. This figure shows the angular dependence (angle between the line of sight and the magnetic field direction) of gyroresonance opacity at the three most relevant harmonics, $s = 2, 3$, and 4, for a particular set of densities, and for a temperature $T = 3 \times 10^6$ K. The opacity is linearly proportional to electron density, n_e , and depends on temperature as T^{-6-1} (as T for $s = 2$, T^2 for $s = 3$ and so on), so these curves will move up or down in the figure for different n_e and T .

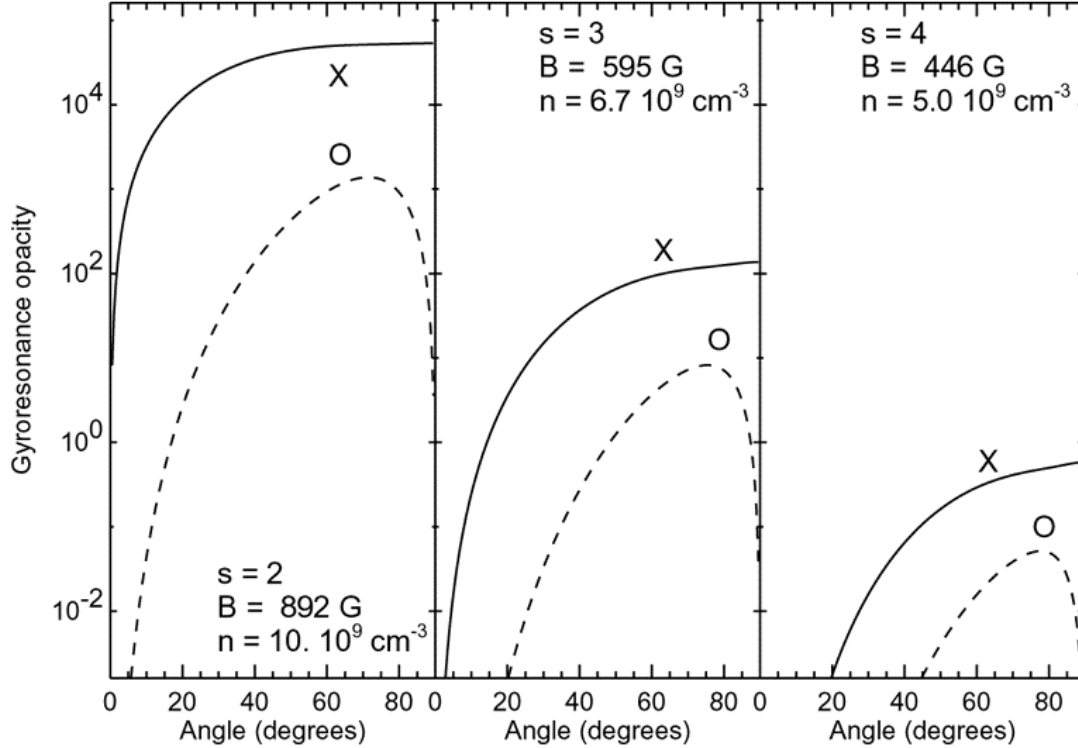


Figure 1: Optical depth of the $s = 2, 3$, and 4 gyroresonance layers at 5 GHz as a function of the angle θ between the line of sight and the magnetic field direction. The atmospheric model used has $T = 3 \times 10^6$ K and a magnetic scale height of 10^9 cm. In each panel the solid line is the optical depth of the layer in the x mode while the dashed line is the optical depth in the o mode. From White and Kundu (1997).

The *key point* of this figure is that the harmonics are *well separated* in opacity. In going from harmonic 2 to 3 (left panel to middle panel), the opacity drops by two orders of magnitude, and likewise in going from harmonic 3 to 4 (middle to right panel). This means that which harmonic is optically thick is highly *quantized*. For a given active region (given temperature and density structure), a harmonic layer is likely to be either optically thick over a wide range of angles, or optically thin everywhere.

The curve labeled “X” in the figures can be (to a good approximation except near $\theta = 90^\circ$) considered to represent one circular polarization, while the curve labeled “O” represents the opposite circular polarization. Thus, measurements in the two circular polarizations provide two separate probes of each line of sight. Note that at small angles to the line of sight the opacity

drops significantly. This leaves an “opacity hole” through higher harmonic layers, allowing lower layers to be seen. This is a complication, but one that can be exploited to give precise measurements of the angle of the magnetic field in certain parts of the active region.

Temperature on Isogauss Layers

Consider imaging observations of an active region at a single frequency, f . On those lines of sight where the magnetic field strength is at least $B = f/2.8 \times 10^6$ s, ($= 119 f_{\text{GHz}}$ G) the corona will be optically thick and the brightness temperature will be equal to the electron temperature in the corona at that location. Ignoring the angular dependence for the moment, the radio emission gives a map of coronal temperature on an isogauss layer of known field strength. An illustration showing these isogauss layers at three observing frequencies for an actual active region, calculated from a photospheric field extrapolation, is given in Figure 2.

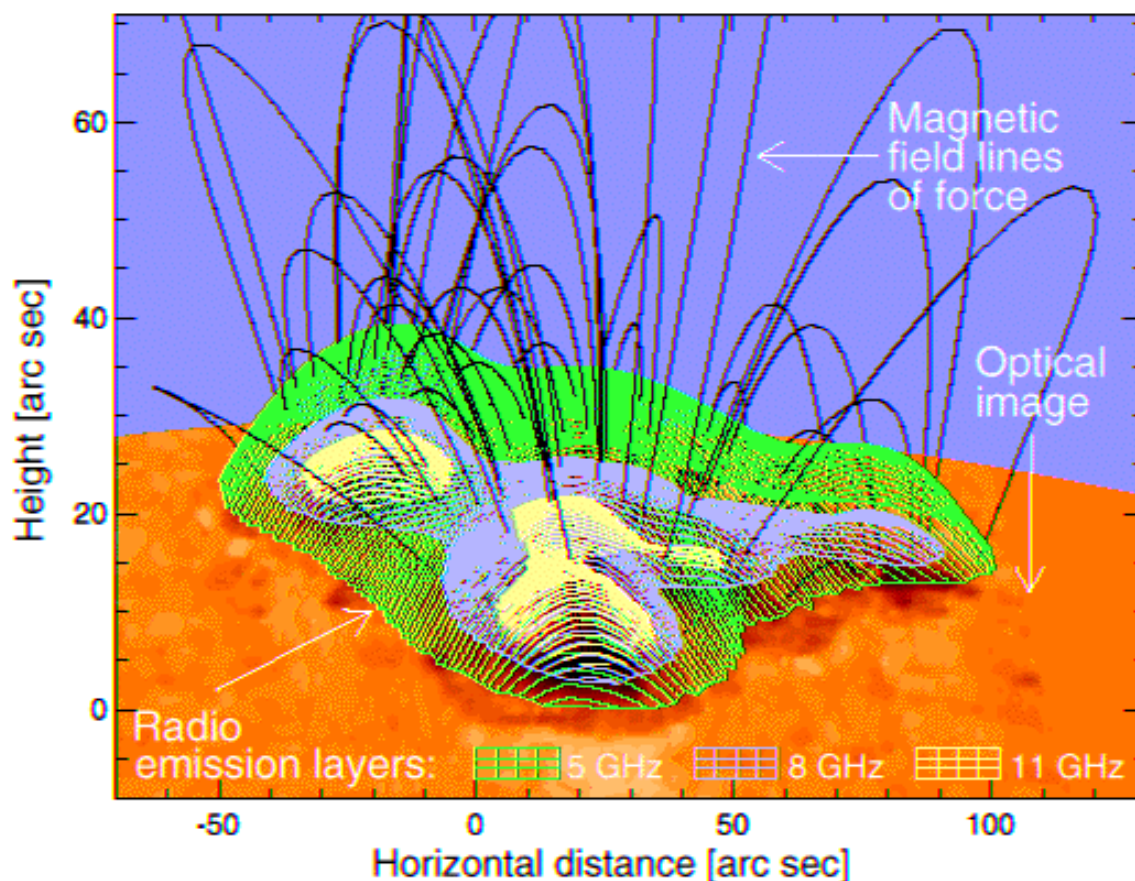


Figure 2: A perspective view of a complex sunspot group (7 May 1991) in optical continuum is shown with field lines extrapolated into the corona using a nonlinear force-free extrapolation by Z. Mikic. The three surfaces are the calculated gyroresonant surfaces in the corona that will dominate the radio opacity at each of three radio frequencies: 5 GHz ($B = 600$ G), 8 GHz ($B = 950$ G) and 11 GHz ($B = 1300$ G). (Produced by Jeongwoo Lee/NJIT.)

Actual VLA observations at three frequencies are shown in Figure 3, from Lee et al. (1997), for the same active region. Note that these are the *only* three frequencies observable with the VLA that are relevant to coronal magnetography. FASR will obtain images at about 3 times this spatial resolution, and at hundreds of frequencies over this frequency range.

Coronal Magnetography with FASR

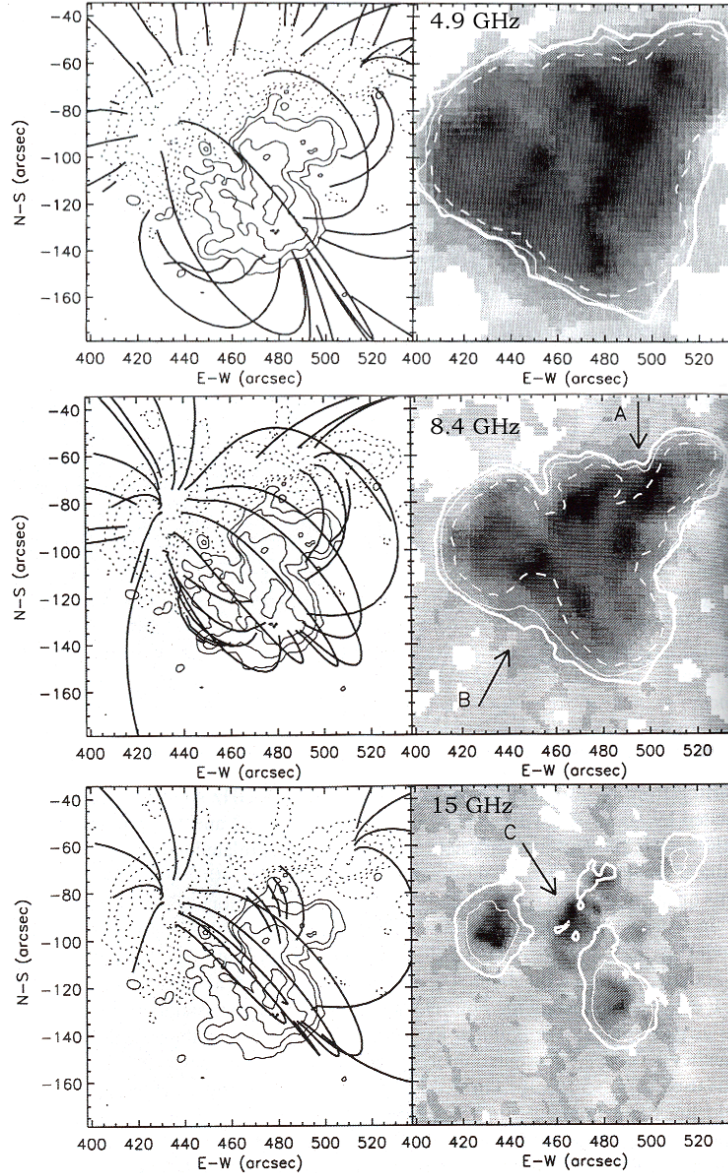


Figure 3: VLA observations of the active region of Figure 2, at three frequencies. The left panels of each row give selected field lines from a potential field extrapolation from photospheric fields. The gray-scale images in the right-hand panels show the radio brightness at 4.9 GHz (top), 8.4 GHz (middle), and 15 GHz (bottom), with contours showing the expected location of the boundary of each map. Dashed contours give the boundary from an uncorrected magnetogram. The thin and thick solid contours give the boundary location after correction for stray light and saturation effects, and extrapolated to heights of 4400 and 2900 km, respectively. From Lee et al. (1997).

The brightness variation over the source, shown by the gray-scale images at right for each frequency, is complicated. There are bright spots and dim spots that do not seem to be obviously related to the magnetic field. These are due to the varying coronal temperature on this isogauss layer. The height of this layer is, of course, highly variable over the active region. However, our method for practical coronal magnetography *does not depend on the interior brightness temperature* of the radio source. Rather, it uses the outer boundary of the source at each

frequency. This boundary is the location of a *rapid drop in temperature*, from values characteristic of the corona ($> 10^6$ K) to values characteristic of the chromosphere ($< 20,000$ K). Although points along this boundary are at an indeterminate height, the thinness of the transition region ensures that the height is relatively constant. As an example, the white contours in Figure 3 show the expected boundary of radio emission obtained from the photospheric magnetogram (dashed line) and the potential field extrapolation at two heights (4400 km—thin solid line and 2600 km—thick solid line). The comparison between the outer boundary of the radio emission and the field extrapolation contours is excellent except at the highest frequency where the details of field direction, coronal temperature and density structure becomes critical to the interpretation. Our experience so far has been with limited spatial resolution of 5–10". *TRACE* has shown that the transition region is highly structured on scales of 1" or less. One might expect that *FASR*, with its higher spatial resolution of 1–4 ", will find that the outer (temperature) boundary of the source is highly convoluted. However, this boundary represents temperature at constant field strength, with *no* density dependence (assuming the emission is optically thick), so it remains to be seen how structured such a boundary will be.

A Practical Coronal Magnetograph

The observational approach for a practical coronal magnetograph is to obtain high-resolution images at many radio frequencies and simply plot the location of the outer boundary (defined as a particular brightness temperature) versus frequency. The reason that this works is as follows: (1) A particular observing frequency picks out a particular isogauss layer, fixing B . (2) An isothermal contour in this isogauss layer then fixes T , thereby picking out places in the corona where the both B and T are constant. (3) By choosing a temperature corresponding to the thin transition region, we minimize the height variation.

Assuming that $s = 3$ is the highest optically thick harmonic, a boundary from an image at frequency f represents the magnetic field strength contour $B = f/2.8 \times 10^6 s = 119 f_{\text{GHz}}$ gauss. The range of magnetic fields covered by *FASR*, whose frequency range is 0.3–30 GHz, thus nominally corresponds to $36 \text{ G} < B < 3570 \text{ G}$. However, due to the temperature and density structure of the solar corona, the second of our list of emission mechanisms, free-free emission, is expected to dominate below 1–2 GHz in many (but not all) places in an active region. Thus, the more likely lower limit to B is about 200 G. The resolution in field strength is the same as the resolution in frequency, around 3%. It is possible, although it has not been shown, that the $s = 4$ harmonic layer may be measurable, even though in most places it may be optically thin. If so, the field strength would correspond to about 150 G.

Potential Limitations

There are several situations where the above approach will lead to errors that will limit its use. These include:

- The method assumes that the brightness temperature boundary corresponds to the base of the corona. This is true along the entire boundary only if the region is near disk center. As the region approaches the limb, the top of the isogauss surface will occult the limbward side of the boundary. At the limb, however, the top of the isogauss surface is seen in profile, and the height can be measured directly. Thus, the interpretation of parts of the boundary changes with distance from the limb, but still may be a useful measure of coronal field strength.
- The discussion above assumed that the highest optically thick harmonic is the same ($s = 3$) along the entire boundary. In reality, parts of the boundary may belong to $s = 2$ or 4. In practice, the relevant harmonic can be determined directly from the data (by examining the polarization spectrum), so this is not expected to limit the usefulness.

- In our discussion, we have ignored the angle of the magnetic field. At those parts of the boundary where the field direction is closely aligned (say within 10°) to the line of sight, the opacity may be so low that no harmonic is optically thick. This will occur for some active regions at some frequencies, and for these active regions will leave a relatively small “hole” of ambiguity in the magnetic field maps.

What Use Are Coronal Magnetograms?

Given that *FASR* could make coronal magnetograms only in active regions with relatively strong magnetic fields greater than about 200 G, what use are they? In fact, they are key to several important kinds of information about the solar corona. First, they can be used as an independent test of photospheric field extrapolations. Second, differences between coronal magnetograms and potential field extrapolations pinpoint the location of coronal currents, as has already been shown by Lee et al. (1998). Measurement of the field-aligned force-free currents will make it possible to establish better non-linear force-free field extrapolations, which can then quantitatively extend the field to lower field regions. Third, they can be used to locate current sheets. The extra information about the spatial distribution of coronal temperature on each isogauss surface can be used to relate regions of coronal current to plasma heating. Fourth, the snapshot imaging capability of *FASR* will allow it to follow extremely dynamic changes in field strength, coronal current location, and signatures of heating, and will thus be of great interest to pre- and post-flare studies.

Why Has This Not Been Done Before?

The short answer to this question is that *the right instrument has never existed to do it*. As should be clear from the above discussion, the basic observation needed to make the technique work is high-spatial-resolution imaging at many closely-spaced frequencies over a wide frequency range. The VLA provides nearly adequate imaging (at least when averaged over several hours of integration), but at only three useful frequencies. A number of very interesting results have been obtained using the VLA (e.g. Lee et al. 1997; Lee et al. 1998ab), sufficient to prove the efficacy of the technique, but these are far from what is required for daily high-quality coronal magnetograms because: (1) the snapshot image quality of the VLA is not sufficient to image complex active regions, (2) the VLA is not solar dedicated, and (3) the number of frequencies are too few and spaced too wide apart to give sufficient magnetic field resolution, or to allow unambiguous determination of the relevant harmonic. The Owens Valley Solar Array (OVSA) has nearly the required frequency resolution, but the images are too crude to make detailed coronal magnetograms. Again, a number of interesting OVSA results have been published (e.g. Lee et al. 1993ab; Gary & Hurford 1994), sufficient to prove the technique. All we require for daily, detailed, high-precision coronal magnetograms is a solar-dedicated instrument that has sufficient spatial and spectral resolution, plus sufficient snapshot image quality over the relevant spatial scales. *FASR* is designed to fulfill these requirements.

Other Approaches to Measuring Magnetic Fields

FASR is designed to do much more than simply obtain 2D coronal magnetograms. It will obtain images and spectra of other types of radio emission, which, as mentioned in the introduction, are each sensitive to magnetic field strength. Optically thin free-free emission has been used to measure magnetic fields in weak field regions both near the limb, and against the disk (Grebinskij et al. 2000), exploiting the $B \cos \theta$ dependence of free-free polarization. This could be used to extend coronal magnetic field measurements near active regions to lower field strengths of perhaps 20-30 G. Problems include the facts that the measurement is a weighted average over a long line of sight and only the longitudinal field is determined. A more promising technique for

weak fields is to use polarization inversions due to *quasi-transverse* (QT) propagation, which is the only sensitive technique to measure fields at heights of $10^4 - 10^5$ km. This has been exploited by Lee et al. (1998b) and Ryabov et al. (1999), and serves as a powerful constraint to magnetic field extrapolations. Finally, we mention that *FASR* observations of network elements should be useful for measuring the expansion of the associated canopy fields, although actual measurement of the field strength through free-free polarization is less likely.

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