MEASUREMENT OF CORONAL FIELDS USING SPATIALLY RESOLVED MICROWAVE SPECTROSCOPY

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INTRODUCTION

As large interferometers have become available for solar use, observation of active regions at microwave frequencies have been obtained with sufficient resolution to resolve the sources of interest. Such observations have shown that some of the active region emission is in the form of small sources with coronal brightness temperatures which are often (but not always) located near sunspots. The emission mechanism of gyroresonance opacity has been shown to account for such sources in most cases (*e.g.* Alissandrakis, Kundu and Lantos, 1980; Chiuderi-Drago et al. 1982; Lang, Willson and Gaizauskas, 1983). At intermediate microwave frequencies, ~ 5 GHz, where these sources are most readily observed, the corona is normally optically thin. However at the height and location where the observing frequency is a low harmonic of the local gyrofrequency, this mechanism can render the corona optically thick. The contrast between the 10^6 K brightness temperatures so achieved and the optically thin value of a few times 10^4 K is readily observable with interferometers. Such observations then identify the locations at which there is at least one height in the corona where the magnetic field has a value which can satisfy the resonance condition corresponding to the observing frequency.

An alternate approach to the study of active regions involves the use of microwave spectroscopy. From this perspective, gyroresonance opacity can be shown to introduce sharp breaks in the microwave spectra at frequencies corresponding to low harmonics of the gyrofrequency at the base of the corona, In this case, the magnetic field information refers to a specific height. Observations with relatively low spatial resolution but good spectral resolution have confirmed the expectations of such a picture (Hurford, Gary and Garrett, 1985, hereafter HGG).

In this paper, we consider the potential implications of observations which combine both high spatial and high spectral resolution. In particular, we will be interested in the ability to measure the magnetic field at the base of the corona on a point by point basis, as in a true magnetograph. In the next section, we present model calculations of the microwave brightness temperature spectrum along specific lines of sight near a sunspot. Subsequent sections will present corresponding observations.

MODELLING THE MICROWAVE SPECTRUM

To calculate the expected form of the microwave spectrum in the presence of strong magnetic fields, we assume a spherically symmetric solar atmosphere in which the temperature and density varies with height in accordance with a constant conductive flux model. The magnetic field was assumed to be a potential field generated by a vertically-oriented magnetic dipole buried below the photosphere. It is worth noting that the model is not formulated in terms of specific loops. Thus the spectral features that emerge below are a consequence of the convolution of the resonant character of gyroresonance emission, the steep temperature gradients at the base of the corona, and smoothly varying magnetic fields.

At each frequency and polarization, curves of growth were calculated along lines-of-sight using the MCMEM code (Magnetic Corona Microwave Emission Model) (HGG). The calculation took full account of free-free thermal bremsstrahlung (including magneto-ionic effects) and gyroresonance opacity. Combining results for integrations at different frequencies yielded brightness temperature spectra such as shown in Figure 1 for a typical line-of-sight.

Referring to Figure 1 we see that coronal temperatures are achieved at low frequencies. At high frequencies the resulting temperatures are much lower since the free-free optical depth of the corona is small and the gyroresonance condition is satisfied only in the chromosphere or below. Of most interest in the present context, however, are the sharp drops in brightness temperature at different frequencies in the two senses of circular polarization.
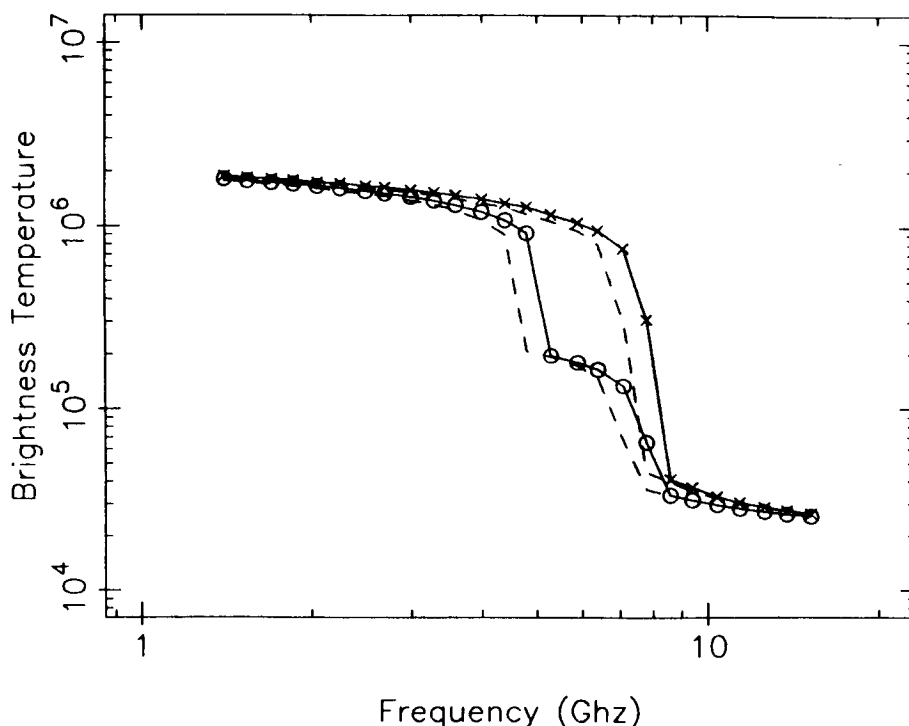
Figure 1. The crosses and circles show model spectra along a line of sight in extraordinary mode and ordinary mode respectively. The solid lines represent spectra for a magnetic field strength that is 10% larger than that assumed for the spectra shown by the dashed lines.

Under coronal conditions, the gyroresonance opacity at successively higher harmonics typically drops by at least an order of magnitude so that the coronal opacity at a given frequency/polarization is often dominated by emission at a single harmonic. Thus it is useful to think of this emission as coming from a single atmospheric layer (an isogauss surface) in which the field satisfies the resonance condition. As the frequency is increased, the magnetic field corresponding to this resonance layer must increase proportionately. For fields which decrease monotonically with height, this means that the height of emission decreases as frequency increases. Interpreting the frequency axis as a rough height scale, the sharp drop in brightness temperature occurs when the resonance layer reaches the transition zone.

The fact that the drop occurs at different frequencies at in right- and left-circular polarization can also be explained by this picture. Since the opacity differs significantly between the ordinary and extra-ordinary propagation modes, the dominant harmonic is not necessarily the same in the two modes. Thus the resonance condition at the base of the corona is satisfied at different harmonics and so at different frequencies in right- and left-circular polarization.

Figure 1 also illustrates that the primary effect of enhancing the magnetic field strength by 10% is to shift the curves in frequency by 10%. Thus the frequency at which the discontinuity occurs (particularly in the extraordinary mode) can be interpreted in terms of the resonance condition at the base of the corona This suggests that such spectra could be interpreted in terms of the magnetic field strength at the base of the corona. We now turn to the observations to judge whether these arguments are applicable in practice.

OBSERVATIONS

The Owens Valley frequency-agile interferometer (Hurford, Read and Zirin, 1985) was used to observe an isolated sunspot at 56 frequencies between 1.4 and 12 GHz in both right and left circular polarization. The observations, discussed in more detail elsewhere (Hurford, 1986) were obtained with the interferometer in its 3-element configuration which has sufficient resolution to enable the emission to be resolved at all frequencies. The single sunspot would be expected to provide a single, symmetric source of gyroresonance emission. Observations for which phase closure was not consistent with this expectation were rejected. In

practice, this procedure excluded the high and low frequency data for which free-free emission played a larger role. Given a single symmetric source, the ratio of amplitudes observed with different baselines could be directly interpreted in term of source size, which is defined as the FWHM of the equivalent gaussian. The availability of 3 baselines provided a redundant amplitude which helped confirm the appropriateness of a gaussian source profile. The ratio of flux to source size also yielded the brightness temperature at each frequency and polarization. **Figure 2 shows the observed size and brightness temperature spectra.**
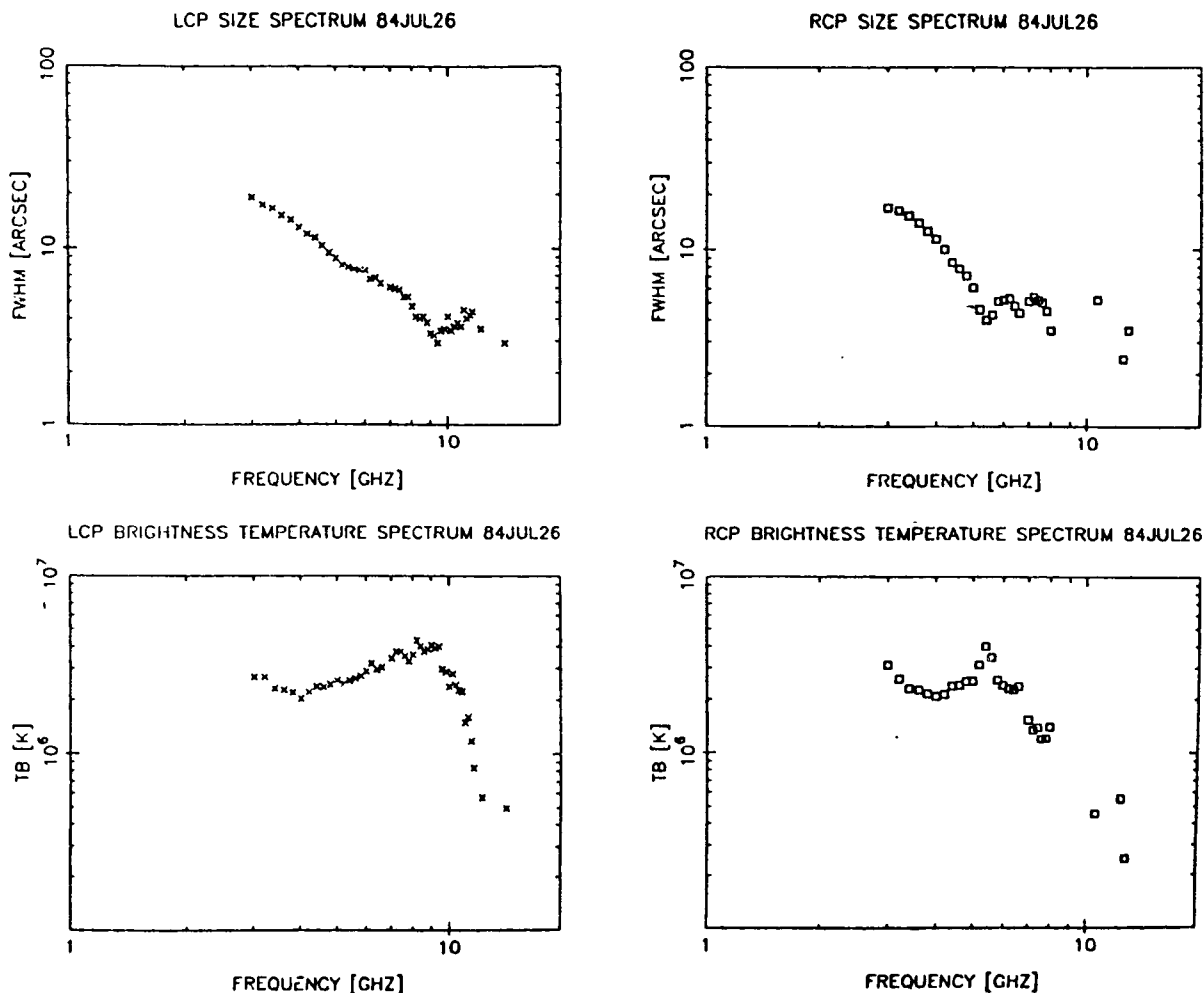

Figure 2. Size and brightness temperature spectra obtained for an isolated sunspot.

To compare the observations with the spectra in Figure 1, it is necessary to deduce the brightness temperature spectrum as it would be observed along specific lines of sight. Formally, the appropriate technique is to synthesize complete brightness temperature maps at each frequency. Then the brightness temperatures would be noted at a common location of interest in each map. In the present circumstance, we can use an abbreviated version of this procedure by exploiting the expected azimuthal symmetry of the source. We further assume that the centroid of each source is directly over the sunspot, an assumption that is reasonable given the isolated nature of the spot and its location near disk centre. These assumptions and the observations shown in Figure 2 define the source brightness temperature at each location. Following the procedure illustrated schematically in Figure 3, we can then deduce the brightness temperature spectrum at any desired radial displacement from the centre of the sunspot.

A typical spectrum is illustrated in Figure 4. It represents an observational determination of the microwave brightness temperature spectra along a specific line-of-sight, in this case toward a location 4000 km from the centre of the sunspot. As such, it can be directly compared to the model spectra in Figure 1.
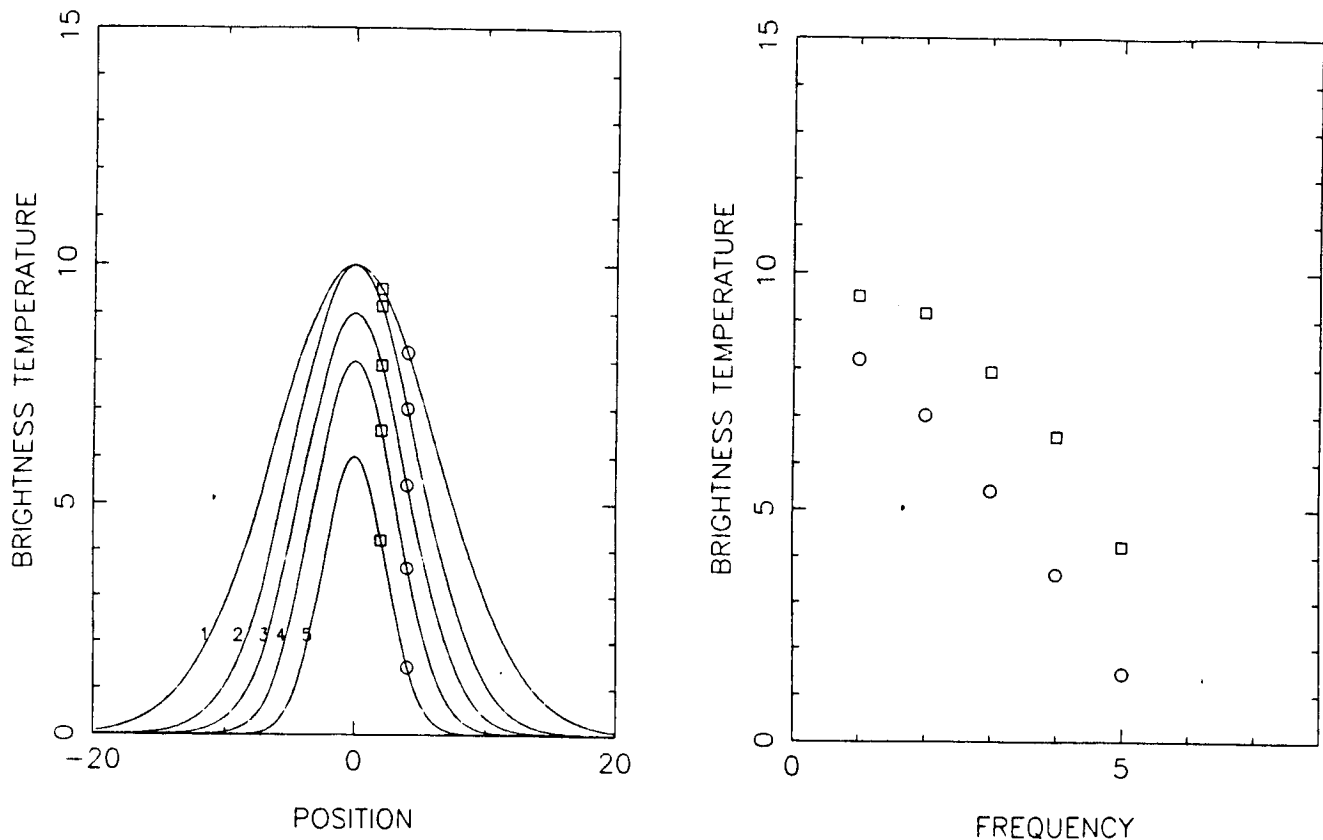
Figure 3. Schematic illustration of how size and brightness temperature spectra are converted to line-of-sight spectra in the case of a single gaussian source. In the left panel, spatial profiles based on size and brightness temperature parameters, are shown for 5 frequencies. At 2 positions of interest (squares and circles), such profiles then yield the line-of-sight spectra (at a single polarization) shown at right.

DISCUSSION

The comparison shows that the observed spectrum shares most of the principle features found in the model spectra. In particular the coronal brightness temperatures at low frequencies, the much lower values at high frequencies and the rapid dropoff in brightness temperature at different frequencies in right and left circular polarization. The observations even show the more complex form of the dropoff in the ordinary mode. Although there are quantitative differences between Figures 1 and 4, no attempt was made to adjust the model parameters to match this particular data set. Nevertheless, the correspondence provides confidence that such spectra can be interpreted to yield the value of magnetic field at the base of the corona. In the case illustrated, the magnetic field at the base of the corona at a radial displacement of 4000 km were found to be 900 g, to a precision of a few percent. Corresponding spectra yield the magnetic field at different radial displacements and so could provide the radial profile of the field at the base of the corona.

These considerations suggest that microwave spectroscopy can be used to deduce position dependence of the magnetic field at the base of the corona, much in the manner of a coronal magnetograph. Gary and Hurford (1986) have exploited a partial solar eclipse to apply microwave spectroscopy for a more complex region. They also found that in the absence of strong magnetic fields, the spectra of free-free emission could be interpreted in terms of loop temperature and density.

We believe that spatially resolved microwave spectroscopy provides a promising new coronal diagnostic. At present, however, a key limitation in its application is the lack of sufficient number of antennas with which to map complex active regions.
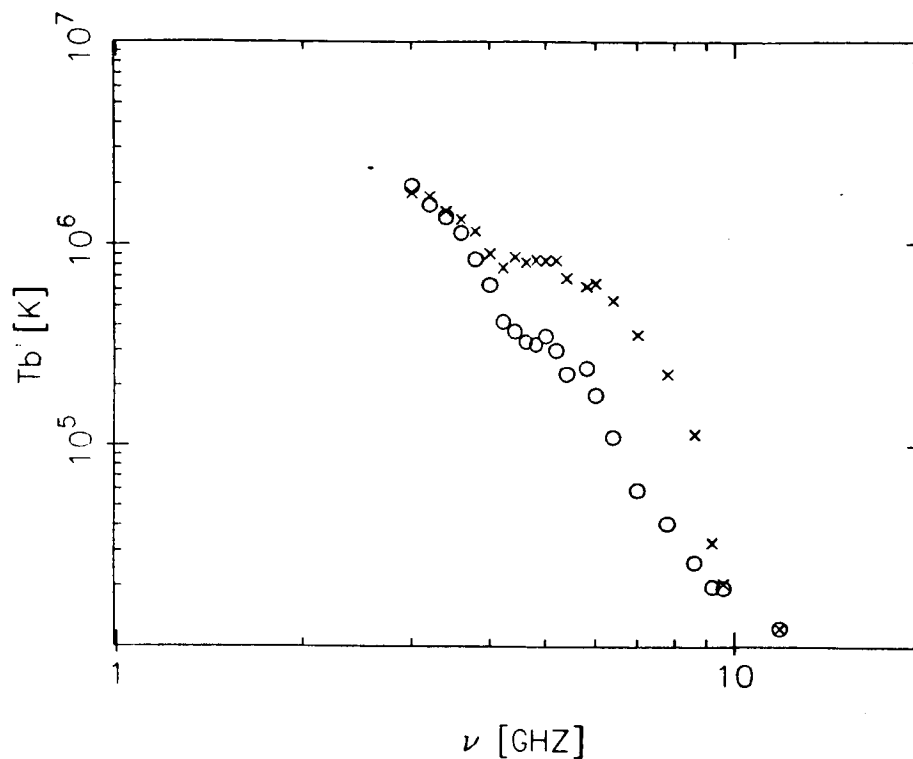
Figure 4. Typical line-of-sight brightness temperature spectra in left- and right-circular polarization (crosses and circles) deduced from the data shown in Figure 2 using the method illustrated in Figure 3.

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