

2nd *Advances in Solar Physics Euroconference*
Three-Dimensional Structure of Solar Active Regions
ASP Conference Series, Vol. 155, 1998
C. E. Alissandrakis, and B. Schmieder, eds.

The Solar Atmosphere Above a Sunspot

E. Ya. Zlotnik

Inst. of Applied Physics, 46 Uljanov St., 603600, N. Novgorod, Russia

S. M. White & M. R. Kundu

Dept. of Astronomy, University of Maryland, College Park MD 20742

Abstract. Using high-quality VLA observations of an isolated simple sunspot near disk center, we derive a model for the electron temperature and density in the atmosphere above the sunspot which reproduces the radio data. The images at 5 and 8 GHz show a classic ring structure. An important result of the model is that there must be cool dense plasma present in the atmosphere over the center of the sunspot.

1. Introduction

Radio emission from regions of strong magnetic field in the corona above active regions is dominated by gyroresonance opacity. Gyroresonance emission arises due to the acceleration which produces the spiralling motion of electrons in a magnetic field. The opacity depends in principle on the magnetic field, the electron density and the temperature. However, being a resonant mechanism, the emission pattern is simplified: emission arises in very thin layers of constant magnetic field strength, B , corresponding to the resonance $f = 2.8 \times 10^6 sB$ GHz, where s is an integer. Furthermore, under normal coronal conditions the optical depth varies by a factor of order 10^3 from one harmonic resonance layer to the next. Thus generally we only need to consider the highest (i.e., largest value of s) optically thick layer: the observed brightness temperature represents the electron temperature on this layer.

There are actually two natural modes in the plasma corresponding to different polarizations, which are generally observed as opposite circular polarizations. The two modes are the extraordinary (x or E) and the ordinary (o) modes: the electric vector of the x mode rotates in the same sense as the electron does, and thus interacts more strongly with radiation (i.e., has higher opacity) than does the o mode. For this reason, the x mode is generally optically thick in the $s = 3$ layer but not the $s = 4$ layer, while the o mode is optically thick in the $s = 2$ layer but no higher layers. An additional effect which must be taken into account when interpreting the radio images of gyroresonance emission is that the opacity is quite a strong function of viewing angle, particularly in the o mode: opacity is maximum at viewing angles nearly orthogonal to the magnetic field in the source and minimum when viewed along the magnetic field direction. This has the effect that the harmonic layer which is optically thick at the edges

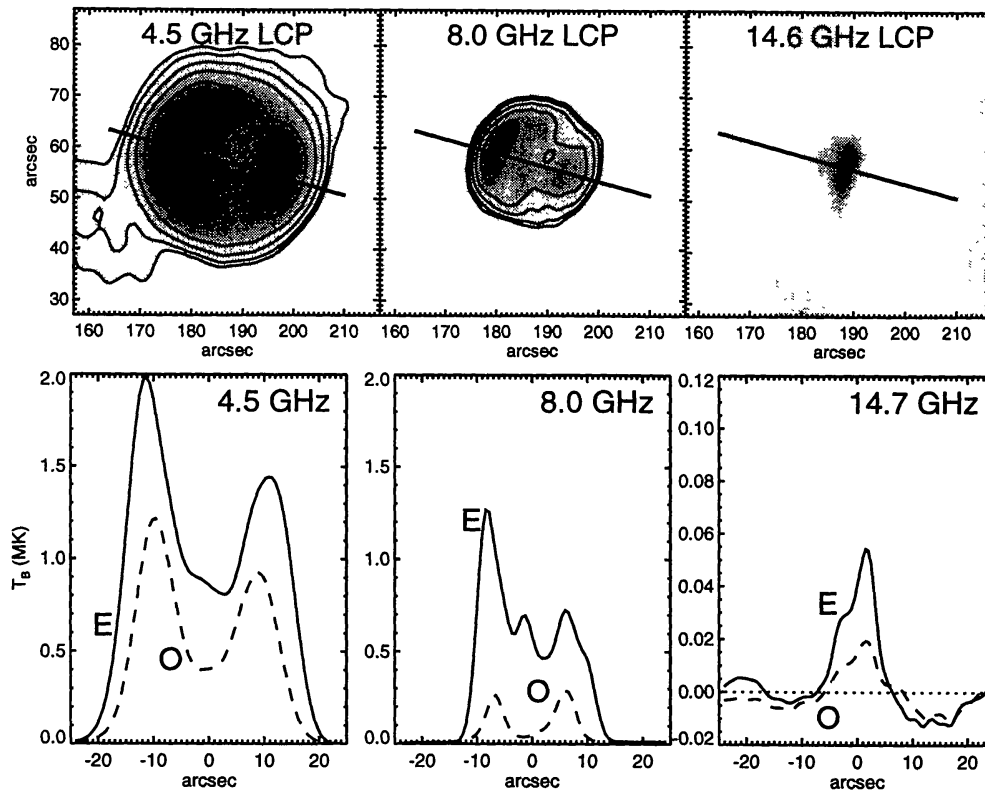


Figure 1. (top panels) VLA images of a sunspot observed on 1994 October 15 at 4.5 GHz (left), 8.0 GHz (middle) and 14.7 GHz (right). Contours are plotted at brightness temperature levels 60, 100, 200, 400, 800, 1200, 1600 & 2000×10^3 K. The images shown are the extraordinary mode; the ordinary mode images are similar in morphology but somewhat less bright. The restoring beam sizes in the images are $5''.6 \times 4''.7$ at 4.5 GHz, $3''.5 \times 2''.7$ at 8.0 GHz, and $3''.9 \times 1''.5$ at 14.7 GHz. (lower panels) Plots of brightness temperature T_B versus position for cuts across the images along the line shown above. The extraordinary (labelled E in this figure) and ordinary (O) mode cuts are shown at 4.5 GHz (left panel), 8.0 GHz (middle panel) and 14.7 GHz (right panel). Note that the vertical scale is the same on the left and middle panels, but is greatly expanded in the right panel.

of the source where the viewing angle is largest may become optically thin at small viewing angles, in which case a lower harmonic layer becomes the highest optically thick layer.

The dependence of the opacity on B , n (electron density) and T (electron temperature) is very well understood (e.g. Zlotnik 1968). Given models for B , n and T , radio emission maps may easily be calculated at any frequency desired. Conversely, given radio images at a number of frequencies, a great deal of information on physical conditions in the solar atmosphere may be derived. In this paper we take high-dynamic-range images obtained at three frequencies

with the Very Large Array (VLA) radiotelescope¹ and derive model electron density and temperature distributions which match the observations. The target is a simple well-isolated sunspot not far from disk center. We are unable to derive all the physical parameters from these radio data, so we assume that the sunspot magnetic field is well represented by a dipole field. Vector magnetogram observations of the spot are consistent with such an assumption. Knowledge of the magnetic field allows us to extract the density and temperature from the data. There is not sufficient space in this report to discuss all the details of the analysis: these are presented elsewhere (Zlotnik, White & Kundu 1998). Here we present the final model which fits the data and discuss the implications of the results.

2. Radio Images of a Sunspot

The radio images of the sunspot in the x mode at 4.5, 8.0 and 14.7 GHz together with one-dimensional cuts through the sunspot in both modes along a line joining the maxima in brightness are shown in Figure 1. The radio source is remarkably round and quite symmetric at 4.5 GHz, whereas at 14.7 GHz the emission is restricted to a small region over the umbra and is much weaker than at the lower frequencies. Since the peak brightness temperature at 14.7 GHz is only about 50000 K, it is clear that none of the gyroresonant surfaces are optically thick in the corona at 14.7 GHz. At the lower frequencies the ring-shaped morphology, first observed by Alissandrakis & Kundu (1982), is expected theoretically for a spot viewed at disk center because of the low opacity at the center of the spot where the field lines are parallel to the line of sight.

3. A Model for the Sunspot Atmosphere

Most previous attempts at modelling of a sunspot atmosphere have assumed plane-parallel density and temperature distributions. Here, the availability of images in three different frequencies places quite strong constraints on the possible models for T and n and allows us to consider more realistic models. We cannot model structure on a spatial scale smaller than the resolution of the images and consequently we assume solutions of analytic form smooth on scales of several arcseconds. The magnetic field is assumed to be represented by a vertical dipole buried below the photosphere. We assume a maximum surface field strength of 2500 G, based on reports in *Solar Geophysical Data*. We then require that the depth of the dipole be such that the radii for the $s = 3$ gyroresonance surfaces for 540 G and 950 G (i.e., the distance from the center of the umbra at which these surfaces drop below the corona) match the observed radii in the radio images at the corresponding frequencies, 4.5 GHz and 8.0 GHz respectively. This leads to a depth of 11000 km for the dipole. The temperature model has an exponential height dependence with a scale height of 2500 km from 10^4 K to

¹The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

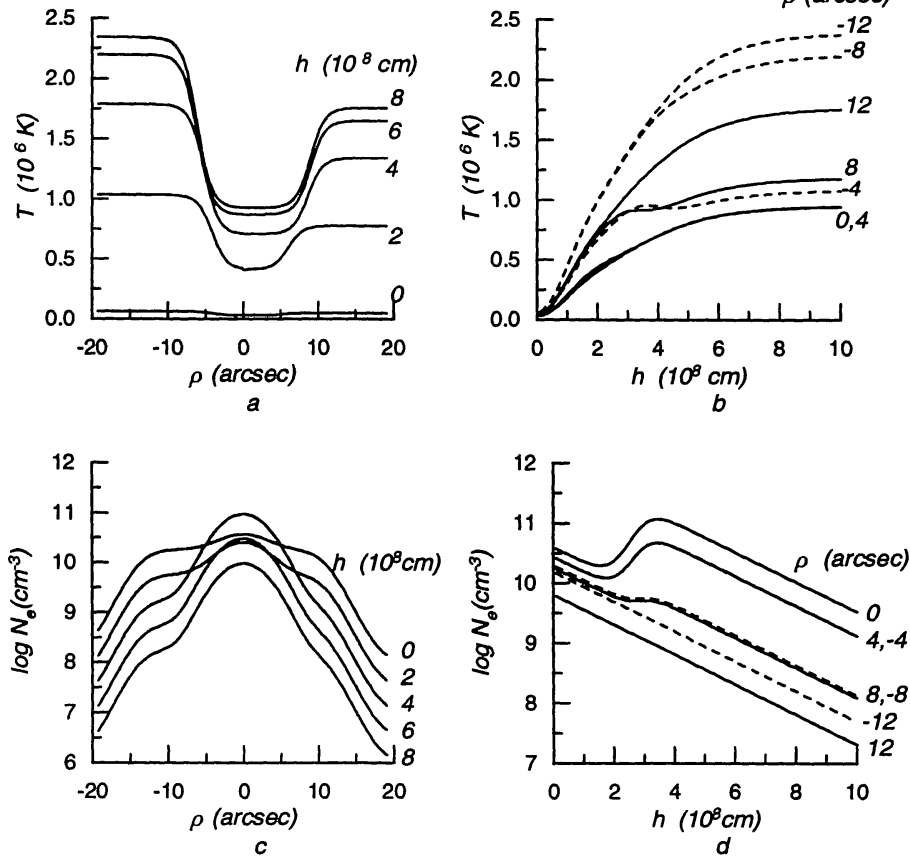


Figure 2. A model of the sunspot atmosphere which fits the cuts shown in Figure 1. The four panels show T and n as functions of radius ρ from the center of the sunspot (a and c , respectively) and of height (b and d , respectively). The different curves in a and c refer to different heights, as labelled, while in b and d the different curves refer to different radii as labelled (the solid and dashed curves in b and d refer to positive and negative values of ρ , respectively).

the corona, and an exponential dependence on radius outwards from the center of the spot. The electron density similarly has an exponential dependence on height and radius.

An important conclusion which may be deduced directly from Figure 1 is that the brightness temperature depression in the center of the spot which produces the ring morphology is not simply due to the decrease in opacity associated with looking parallel to the magnetic field in the source: in that case one expects that the o mode source should show a large central depression while the x mode source should show only a very small depression (e.g., White & Kundu 1997). Here both modes show depressions of similar size. We must instead attribute this depression to the presence of low-temperature material over the umbra.

A second conclusion is that the electron density should be significantly greater in the center of the sunspot than at its edges. Three factors lead to this result: (i) in simple models the x and o modes have similar opacity and are both optically thick at the outer edges of a gyroresonant source (where the inclination angle is maximum), whereas here we see a substantial difference

between $T_{B,X}$ and $T_{B,O}$ at the outer edges of the radio source. This implies that the gyroresonance layer is optically thin at the outer edge of the source, requiring low density. (ii) The peak in the 14.7 GHz image cannot be due to gyroresonance emission, and instead requires a density peak over the umbra to produce sufficient bremsstrahlung emission to explain the observation. (iii) The dips in T_B observed at the centers of the x and o sources at 4.5 GHz, which remain at coronal temperatures, imply that the relevant layers have significant optical depth even in the o mode, which implies high density above the center of the spot.

The fact that the 4.5 GHz brightness temperatures are much larger than the 8.0 GHz brightness temperatures requires that the temperature gradient be positive with height. This follows from the fact that the 4.5 GHz gyroresonant surfaces correspond to lower magnetic field strengths and therefore greater heights in the corona than the corresponding 8.0 GHz gyroresonant surfaces: since T_B represents the temperature on these surfaces, temperature must increase with height.

A smooth model which fits the multi-frequency brightness temperature profiles in Figure 1 is shown in Figure 2. These models incorporate the features mentioned above: temperature at a fixed height increases from the center of the spot outwards while the density decreases, and temperature increases with height. The sharp gradient seen in panel *a* indicates that the cool material is confined to the atmosphere over the umbra. Bremsstrahlung is included in the comparison of models with data, but is found to have negligible effect on the radio images except at the highest frequencies, where bremsstrahlung from the enhanced density over the umbra accounts for the peaks observed. The radio source at 14.7 GHz is quite highly polarized in the sense of the x mode, which again is consistent with bremsstrahlung from high density gas low in the corona where the magnetic field is quite strong.

In conclusion, we note that the modelling carried out here was only possible because of the availability of images at three frequencies: the lack of any one of the frequencies would have greatly reduced the constraints imposed on the model. With even more frequencies much more detailed models can be derived.

Acknowledgments. This work has been supported by NSF grant ATM-96-12738 and NASA grant NAG-5-6257. We thank V. V. Zheleznyakov for valuable discussions.

References

- Alissandrakis, C. E., & Kundu, M. R. 1982, ApJL, 253, L49
White, S. M., & Kundu, M. R. 1997, Solar Phys., 174, 31
Zlotnik, E. Y. 1968, Soviet Ast., 12, 245
Zlotnik, E. Y., White, S. M., & Kundu, M. R. 1998, ApJ, in preparation.