ON THE SOURCE OF THE SLOWLY VARYING COMPONENT AT CENTIMETER AND MILLIMETER WAVELENGHTS

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Abstract. The general features of the slowly varying component at centimeter and millimeter wave-lengths are explained by magneto-ionic thermal emission. A model of an active region is constructed in which the electron temperature and density profile is based on recent EUV measurements, and the current-free magnetic field configuration is derived from a longitudinal magnetogram and scalar potential theory. In the model, the contributions of the reflected component of the inward extraordinary wave is important in determining the characteristic features of the radio flux and polarization. Emission by the mechanism of resonance absorption does not appear to be a significant factor in this model.

1. Introduction

Observations of the slowly varying component at centimeter wavelengths reveal the following characteristics. The flux density, in many sources, is higher at the longer wavelengths than at the shorter centimeter wavelengths (Tanaka and Kakinuma, 1958a, b; Kakinuma and Swarup, 1962, henceforth called KS), with the peak occurring in the vicinity 6–8 cm, and the degree of polarization is higher at the short centimeter wavelengths (KS, 1962). Zheleznyakov (1962) and KS have reported that, in addition to thermal magneto-ionic emission, radiation by thermal electrons in layers resonant at harmonics of the gyrofrequency, have to be taken into account in order to explain the observed features of the slowly varying component.

In this paper, we examine the characteristics of the slowly varying component, and, in the light of recent data and developments, try to determine the origin of the centimeter and millimeter wavelength emission in active regions. The new information includes a chromospheric-coronal model based on EUV data, a magnetic field configuration derived from measured photospheric fields using scalar potential theory, and measurements of the solar flux and degree of polarization at millimeter wavelengths.

In the analysis to follow we will utilize data taken on different regions at different times so it is not expected that there would be an exact correspondence with the measurements. However, the general features of the radiation from active regions can be inferred from the diverse measurements and our study is a semi-quantitative one applying to the general characteristics of the slowly varying component.
Fig. 1. Portion of full disk magnetogram for 31 October 1971 from Kitt Peak National Observatory. The square encloses the region included in the magnetic field calculations in this paper. The effective resolution is about 6" and the noise level is about 15 G.
2. Observations

Flux and polarization measurements at 9 and 3.5 mm were made with the 36 ft National Radio Astronomy Observatory radio telescope at Kitt Peak.* It was found that well developed sunspot groups showed circularly polarized emission components in the right and left hand sense, correlating with the positive and negative polarity regions of the longitudinal magnetic fields. The observed active regions had effective brightness temperature enhancements over the quiet sun values of several thousand degrees at 9 mm, and several hundred degrees at 3.5 mm. In the most active regions the degree of polarization was about 6% at 9 mm and less than 1% at 3.5 mm, reported earlier by Edelson et al. (1971).

The magnetic field data used in this study were derived primarily from a full-disk map of the longitudinal magnetic field obtained with the 40-channel magnetograph of the McMath Solar Telescope at the Kitt Peak National Observatory.** The 40-channel magnetograph has been described in detail by Livingston and Harvey (1971). The spatial resolution of the magnetogram is generally about 5–6" and the magnetic noise level about 15 G. The spectrum line used was 5324 Å of Fe I whose shape and strength are very similar to the more commonly used 5233 Å line. Since this sunspot was very near the central meridian of the Sun (McMath region 11580, 31 October 1971) the longitudinal field will also be a good description of the vertical component of the total field, at least outside of the sunspot umbra. Figure 1 shows an enlargement of a portion of the full-disk magnetogram for this day. Only the area enclosed by straight lines was used for the magnetic field presented in this paper (see Figure 2). It is known that the Kitt Peak magnetograph underestimates the umbral field due to several causes (Harvey, private communication). Therefore, to obtain a more realistic and self-consistent set of measurements for the whole sunspot the magnetic field in the umbra has been scaled upwards according to (1) Mt. Wilson sunspot field measurement at the center of the umbra and (2) the sunspot model of Beckers and Schröter (1969). Basically, the scheme was to use the Mt.Wilson field at the center to determine a scale factor (equal to the Mt. Wilson value divided by the observed field averaged over the central 9 picture elements). This scale factor then fell to unity at the edge of the penumbra in accordance with the sunspot model of Beckers and Schröter (1969, Figures 7 and 8, Equations (1) and (3)). Although this scheme may have systematic errors, at least a large part of the true sunspot flux will be recovered in a physically reasonable way.

The longitudinal field was computed at different heights assuming a scalar potential although the actual case may be more complicated by chromospheric currents as Nakagawa et al. (1971) and Raadu and Nakagawa (1971) have shown. Since the currents in force free magnetic fields do not contribute significantly to the longitudinal

* The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.

** Kitt Peak National Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
component of the fields, we have neglected them. Finally, the sensitivity of the solutions to 'missed' flux was tested by placing extra magnetic flux at the boundary of the region. For any realistic amount of missed flux, the fields at the upper levels (10000 km height) were decreased by only a few percent.

3. Source Model

In recent years, extreme ultraviolet (EUV) solar observations from space have given new insight into the structure of the chromosphere and corona, and it appears that a quantitative description of the average physical conditions in the solar atmosphere is now possible. We will use a solar atmospheric model that is based on the work done by the Harvard group (Dupree and Goldberg, 1967; Withbroe, 1970; Noyes et al., 1970; Noyes, 1971; Gingerich et al., 1971). The electron temperature and density profile for this model is given in Figure 2, showing both quiet and active regions. Typical active regions have a slightly higher coronal temperature than quiet regions, the active region pressure is about five times the quiet Sun pressure, and the temperature gradient in the transition zone is about five times the quiet Sun value.

At the present time, there is no convenient way to measure the magnetic field in the
chromosphere. Since longitudinal magnetograms contain no information to permit calculating a current from the curl of the field, we assume a current-free magnetic field configuration calculated from scalar potential field theory. This premise appears justified by eliminating any presumptions about a spurious current distribution. Furthermore, the fields measured on a particular day and used in this model, with a slight magnetic scaling, should be representative of many other active regions. Hence, while it is true that currents do exist in the solar atmosphere, the assumption of current-free magnetic fields produces a working model, and qualitatively should give a description of the effect of the magnetic fields on the radio emission. The fields are primarily longitudinal in the active region, and the $z$- or longitudinal component of the field is also plotted in Figure 2.

For the active region representation we superimpose this magnetic field directly over the model of the solar atmosphere described previously. This permitted us to

![Diagram](image)

Fig. 3. The plasma and gyro-frequency as a function of height.

study the behavior of the model, and its sensitivity to slight variations of the parameters in the governing equations which can account for the observed features of the slowly varying component. For our model, we show a plot of the plasma and gyro frequencies in Figure 3, and it is seen that there is a region in the transition zone where the latter is greater than the plasma frequency. The quiet region opacities for several centimeter wavelengths are plotted in Figure 4, which shows that the centimeter and shorter wavelengths become optically thick at heights of the transition region and below.
Fig. 4. The optical depth of the quiet solar atmosphere in the absence of a magnetic field is plotted as a function of height for different centimeter wavelengths.

4. Discussion of Source Model

The inclusion of a longitudinal magnetic field introduces two oppositely circularly polarized normal modes of propagation. The apparent brightness temperature is increased over that expected from thermal free-free emission without a magnetic field, and polarized emission is now observed.

A. MAGNETO-IONIC THEORY

In magneto-ionic theory, for longitudinal magnetic fields, the complex indices of refraction are given by (Ratcliffe, 1959)

$$n_{o,e}^2 = 1 - \frac{X}{1 - iZ \pm Y}$$

+ ordinary mode,

- extraordinary mode,

where $X = f_p^2 / f^2$, $f_p$ is the plasma frequency, $f$ is the observing frequency, $Z = v/2\pi f$, $v$ is the collision frequency ($\sim 50$ Hz in the corona), $Y = f_c / f$ and $f_c$ is the gyrofrequency. In the absence of collisions, it is seen that there is a reflection point for the extraordinary wave at the height where $X = 1 - Y$. When the effect of collisions is included, the index of reflection becomes complex, and cannot be zero for any real
height. However, if $Z$ is small, as it is for the cases of interest, there is a region near the height where $X = 1 - Y$ where reflection occurs. As we shall see, the reflection of waves in the solar atmosphere will have to be considered in the interpretation of the observed radio emission.

For $Z \ll 1$ and $(1 - Y) (1 - Y - X) \gg XZ$, the absorption coefficients are given by KS as

$$K_o = \frac{K_n (1 - X)^{1/2}}{(1 + Y)^{3/2} (1 - X + Y)^{1/2}}$$

$$K_e = \frac{K_n (1 - X)^{1/2}}{(1 - Y)^{3/2} (1 - X - Y)^{1/2}},$$

where $K_n$ is the absorption coefficient for zero magnetic field. The expression for $K_e$ does not hold true near the reflection point, and for that region $K_e$ can be obtained from Equation (1) where $K_e = \omega \Im n_e/c$. The optical depths for the ordinary and extraordinary modes of propagation are given by $\tau_o = \int K_o \, dh$ and $\tau_e = \int K_e \, dh$, and these are plotted in Figure 5 for three representative wavelengths, 10 cm (3000 MHz), 6 cm
(5000 MHz), and 3 cm (10000 MHz). The vertical arrow on the opacity curve of the extraordinary wave for 10 cm marks the height of the reflection point for this wavelength. The brightness temperature is

$$T_b = \frac{1}{2} (T_o + T_e + T_r),$$

where $T_o = \int T e^{-\tau_o} d\tau_o$, $T_e = \int T e^{-\tau_e} d\tau_e$, and $T_r$ is the component due to the reflection of the inward travelling extraordinary wave. Its amplitude and polarization depend on the reflection coefficient and the amplitude is further attenuated during its subsequent traverse through the solar atmosphere out toward the observer. Neglecting the effects of the reflected component, the brightness temperature given by Equation (4) is greater than that expected from thermal free-free emission with zero magnetic field, and if the reflected wave is included, the apparent brightness temperature is increased even further. This might possibly explain the high observed values of $T_b$ at the long centimeter wavelengths (KS, 1962).

B. MAGNETIC FIELD STRUCTURE

The photospheric magnetic field varies throughout the active region and the variation with height is evident in Figure 2. In the regions of interest the magnetic field typically changes several gauss per kilometer of height. In addition to the decrease with height, there is a field variation along the angular direction. This variation effectively determines the source sizes of the radio emission. The region bounded by the half intensity magnetic field is approximately $\frac{1}{2}$' in diameter.

![Graphs](image_url)

Fig. 6a, b. Flux and polarization as a function of height for this model. The effects of the reflected extraordinary wave is not taken into account.
C. FLUX SPECTRUM

The emitted flux from an active region at a particular wavelength is proportional to 
\[ \frac{[(T_b(\lambda) - T_q(\lambda))]/\lambda^2}{}, \] 
where \( T_b(\lambda) \) and \( T_q(\lambda) \) are the brightness temperatures of the active and quiet regions, respectively. Some general characteristics of the flux spectrum can be deduced by examining Figures 2, 4 and 5. As mentioned before, in quiet regions, for wavelengths shorter than 10 cm, most of the emission arises from the transition region where the temperature gradients are steepest and from those layers below this height. In active regions, the increased density and the presence of the magnetic field increases the opacity markedly, especially for the extraordinary wave, at the longer centimeter wavelengths, in the transition zone and corona. The result is that in active regions at those wavelengths, the brightness temperature is increased many times over that of the quiet Sun temperature. On the other hand, at the millimeter wavelengths, the corona is still optically thin and the increase in brightness temperature in active regions, is more modest, of the order of ten percent. It can be seen that for this model, the net increase in brightness temperature at the longer centimeter wavelengths more than offsets the \( 1/\lambda^2 \) dependence, and the maximum in the flux emission occurs somewhere in the centimeter wavelength region. A plot of \( (T_b - T_q)/\lambda^2 \) as a function of frequency is shown in Figure 6a. An increase in magnetic field or electron density shifts the flux maximum toward shorter wavelengths. For example, for an increase of the magnetic field by 25\%, the flux maximum occurs at 7 cm. The inclusion of the reflected component of the inward travelling extraordinary wave raises the flux curve near the maximum, but does not alter the general features of the flux spectrum.

D. POLARIZATION OF THE RADIO EMISSION

The degree of polarization is defined as

\[ P = \frac{T_e - T_o}{T_e + T_o - 2T_q}, \]  

(5)

where \( T_e \) and \( T_o \) are defined as before (Equation (4)), and \( T_q \) is the quiet Sun temperature. A plot of the polarization as a function of wavelength for this model is shown in Figure 6b. Measurements of polarized radio emission at centimeter wavelengths indicate a polarization spectrum that peaks in the short centimeter region (~20–40\%), dropping off at 10 cm (~10\%). At the 9 mm wavelength the measured polarization is of the order of 6\%, and less than 1\% at 3.5 mm. Examining Figure 6b, if our model is a correct one, there should be an explanation as to why the degree of polarization should drop away from a maximum in the short centimeter wavelength region. The dropoff at the longer centimeter wavelengths can be explained by the reflection of the inward travelling extraordinary wave. As the extraordinary wave is reflected near the height where \( X = 1 - Y \), its polarization sense is reversed, and becomes an outward travelling ordinary wave.

Because the magnetic field is not uniform in the angular direction, at a given height, only a portion of the active region is reflective for a given wavelength. At the short
centimeter and millimeter wavelengths, the reflection point occurs deep in the chromosphere. There the atmosphere is opaque for both the ordinary and extraordinary waves, and the reflected wave is not a factor at these wavelengths. For this model, an increase in the magnetic field raises the polarization curve and shifts the maximum toward higher frequencies. If the electron density is increased, the polarization curve is shifted downwards.

Measured polarizations at the millimeter wavelengths are less than that shown in Figure 6b. In addition to the obvious possibility that the antenna used may not be suitable for polarization measurements, a possible explanation for the millimeter wavelength results is the following. It has been found that the brightness temperature in active regions at the millimeter wavelengths is only slightly enhanced over quiet regions, so in the expression for polarization in Equation (5), we have, at the millimeter wavelengths, a quantity that is defined by a ratio of two relatively small quantities. Unpolarized radiation from the surrounding region which is received by the antenna could reduce the measured polarization appreciably. A high resolution antenna with very little cross polarization characteristics would measure higher polarizations at the millimeter wavelengths based on this model.

E. RESONANCE ADSORPTION

For the model used in this paper, the \(2\omega_c\) level for 3 cm wavelength occurs at a level of 1100 km, deep in the chromosphere where the medium is opaque for both the ordinary and extraordinary waves. The \(\omega_c\) level is at 2000 km, in the transition zone. Unless the actual fields are much larger than that used in the model here, resonant emission from the \(2\omega_c\) level for \(\lambda = 3\) cm is not significant. Also, the magnetic field varies in both the angular and radial direction so as to reduce the effective volume of emission at a given wavelength. For example, if we restrict the source to a bandwidth of 200 MHz (\(\pm 100\) MHz), the source diameter at the \(2\omega_c\) level for \(\lambda = 3\) cm is less than 6", and the depth is less than 7 km. At the \(3\omega_c\) level for \(\lambda = 3\) cm, the source diameter is less than 2", and the depth is less than 7 km. The region surrounding the maximum field becomes resonant lower in the chromosphere, but the opacities, \(\tau_e\) and \(\tau_\sigma\), become thicker and reduce the effect of resonance absorption. This can be contrasted to source size of the magneto-ionic emission, which is of the order of \(\frac{1}{4}\)", if we define the size to the half magnetic intensity point. In view of the previous discussion, thermal emission at the harmonics of the gyro-frequency does not appear to be an important factor in the radio emission from active regions in this model.

5. Conclusions

A chromospheric-coronal model is presented in which the temperature and density profiles are based on recent EUV satellite measurements, and current free magnetic field configuration is derived from scalar potential theory. The thermal magneto-ionic emission from such a model is calculated and, with reasonable assumptions, the general features of the emission is consistent with the observed results. In the model, the con-
tribution of the reflected component of the inward travelling extraordinary wave is important in explaining the characteristic features of the flux and polarization. For this model, large magnetic fields as those required for emission by resonance absorption are not necessary. Emission by the mechanism of resonance absorption does not appear to be a significant factor in this model. The reflection of the inward travelling extraordinary mode can also explain the polarization reversal observed in radio bursts at the longer centimeter wavelengths.

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