CYCLOTRON LINES IN THE SPECTRA OF SOLAR FLARES AND SOLAR ACTIVE REGIONS

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Abstract. It was shown by Zheleznyakov and Zlotnik (1980a, b) that in complex configurations of solar magnetic fields (in hot loops above the active centres, in neutral current sheets in the preflare phase, in hot X-ray kernels in the initial flare phase) a system of cyclotron lines in the spectrum of microwave radiation is likely to be formed. Such a line was obtained by Willson (1985) in the VLA observations at harmonics of the electron gyrofrequency. This communication interprets these observations on the basis of an active region model in which thermal cyclotron radiation is produced by hot plasma filling the magnetic tube in the corona above a group of spots. In this model the frequency of the recorded 1658 MHz line corresponds to the third harmonic of electron gyrofrequency, which yields the magnetic field (196 ± 4) G along the magnetic tube axis. The linewidth $\Delta f/f \sim 0.1$ is determined by the 10% inhomogeneity of the magnetic field over the cross-section of the tube; the line profile indicates the kinetic temperature distribution of electrons over the tube cross-section with the maximum value 4×10^6 K. Analysis shows that study of cyclotron lines can serve as an efficient tool for diagnostics of magnetic fields and plasma in the solar active regions and flares.

1. Introduction

Solar microwave emission originating from bremsstrahlung and cyclotron emission of electrons in the inhomogeneous magnetoactive plasma of the solar corona usually has a rather flat frequency spectrum. However, in complicated systems of solar magnetic fields the spectra can have increased complexity, so that under definite conditions they can exhibit fine structure in the form of narrow-band features. A theoretical analysis by Zheleznyakov and Zlotnik (1980a, b) indicates that separate cyclotron lines and high-frequency cutoffs can be resolved in the microwave solar radio emission at cyclotron harmonics. Cyclotron features can form in the sources with different types of kinetic temperature and magnetic field distributions, such as neutral current sheets, regions where the magnetic field along the line-of-sight has a maximum at a certain point and in the magnetic flux tube filled with 'hot' electrons. The frequency spectrum and polarization are specific for each type of distribution. This permits diagnostics of active and preflare regions by observing the form of the fine structure of the microwave spectra.

Detection of cyclotron features and investigation of their source requires two-dimensional images at a number of closely-spaced wavelengths. Willson (1983) was the first who reported the possible detection of thermal cyclotron lines from solar active regions. Indirect evidence for the presence of a cyclotron line in the active region spectrum were obtained by Schmahl *et al.* (1984). Finally, a cyclotron line-like spectrum was observed by Willson (1985) using the VLA at 10 closely-spaced frequencies near 20 cm. Interpretation of this line and diagnostics of magnetic fields in the coronal plasma by its characteristics are proposed by Zheleznyakov and Zlotnik (1988) and in this communication.

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2. Inhomogeneous Magnetic Field Model

According to Willson (1985), a source was situated above a large bipolar group of spots with the linear dimension $2b = 8 \times 10^9$ cm ($\sim 100''$) and a magnetic field $B = 2000$ G at the photosphere. The radio source dimension was $50''$ to $100''$ (the interferometer beamsize was $3'' \times 4''$), the maximum brightness temperature, $T_{b_{\max}}$, was approximately 4×10^6 K at the background temperature $T_c \sim (1.0\text{–}1.5) \times 10^6$ K. The observations were carried out at 10 closely-spaced frequencies between 1440 and 1720 MHz. The frequency spectrum at a chosen point on the source for two days is given in Figure 1. The cyclotron linewidth $\Delta f/f$ was about 0.1 and the line centre was at 1658 MHz. Polarization of the radiation was not observed (within an accuracy of 15%).

The observational data were interpreted by Willson (1985) on the basis of an optically thin source in the thermally-homogeneous model with a constant magnetic field. As will be shown below, the proposed model cannot explain simultaneously the observed line profile, the stability of the parameters and the absence of polarization. There are no such difficulties if the source is optically thick for ordinary and extraordinary modes. The brightness temperature is equal to the kinetic temperature of the plasma in the source, the polarization becomes weak and the line profile and the line width are determined

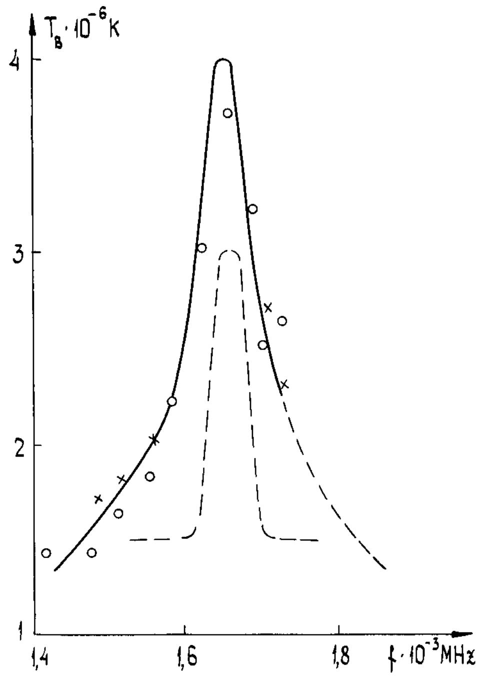

Fig. 1. Cyclotron line in the active region spectrum. The crosses and circles denote the brightness temperatures for two days of observation, recorded by Willson (1985). The solid line is the spectrum of cyclotron radiation of a hot loop with inhomogeneous magnetic field and temperature at the third cyclotron harmonic. The dashed line is the frequency spectrum of a homogeneous hot loop, which we calculated in the homogeneous model.

by the inhomogeneous distribution of plasma temperature and magnetic field in the source.

To analyze this version, we take a model shown in Figure 2. The source is a force tube of bipolar magnetic field, filled with a hot plasma (with the kinetic electron temperature T higher than the surrounding corona temperature T_c), i.e., a hot coronal loop. If the hot plasma pressure is small as compared to the magnetic pressure, then this plasma does not modify appreciably the magnetic field distribution in the plasma. The overall hot loop radiation shows no cyclotron lines because of the inhomogeneity of the field along the tube. Cyclotron lines can appear only if the antenna beam is narrow enough to cut out a region with a quasihomogeneous (in the plane perpendicular to the line-of-sight) magnetic field from the loop. Then the frequency spectrum of observed radio emission may contain cyclotron lines $f = sf_{B_0}$ ($s = 2, 3, 4$ are harmonic numbers, $f_{B_0} = eB_0/2\pi mc$ is the electron gyrofrequency, B_0 is the magnetic field at the centre of the loop). At the second harmonic the cyclotron line contains only an ordinary mode

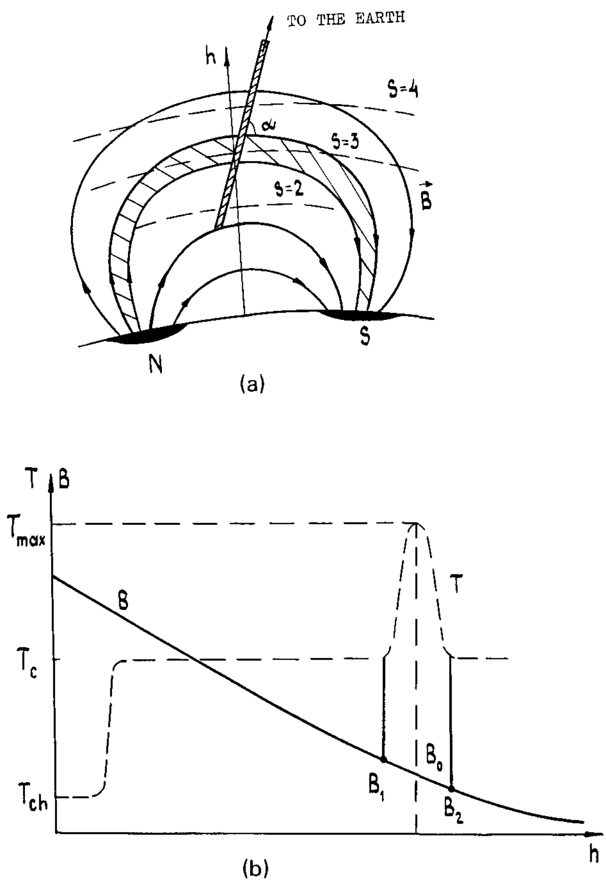

Fig. 2. Qualitative model of a source with hot electrons filling the magnetic flux tube (hot loop): (a) field lines, the loop (large hatching) and antenna pattern (small hatching); gyroresonant layers $s = 2, 3, 4$ (dashed lines); (b) magnetic field and temperature distribution versus height.

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completely polarized, while at the fourth harmonic the extraordinary mode dominates. The third harmonic is partly polarized with an excess in the extraordinary mode if its optical depth $\tau_3 < 1$ and is not polarized if the radiative layer is optically thick ($\tau_3 \gg 1$) for both ordinary and extraordinary modes (for details see Zheleznyakov and Zlotnik, 1980a, b).

Since the antenna beam is much narrower than the angular dimension of the bipolar group of spots, the magnetic field variation across the pattern can be neglected. The magnetic field variation along the pattern (i.e., along the line-of-sight) within the hot loop is rather small: the field changes from B_1 to B_2, where $(B_1 - B_2)/B_1 \ll 1$ (Figure 2(b)). This variation is a key to interpretation of the observed cyclotron line. Following Willson (1985), we approximate the magnetic field B above the bipolar group of spots by the field of a horizontal dipole immersed at a depth of $b = 4 \times 10^9$ cm below the photosphere with a magnetic field of $B_{ph} = 2000$ G at the photosphere. Then the dependence of the field B on the height h above the centre of the group is given by

$$B = \frac{B_{ph} b^3}{(b + h)^3} . \tag{1}$$

The frequency at the centre of the cyclotron line, $f = 1658$ MHz at the third cyclotron harmonic ($f = 3f_{B_0}$), corresponds to a magnetic field $B = 196$ gauss, at an altitude $h_3 = 4.7 \times 10^9$ cm, i.e., at the centre of the loop with a maximum temperature $T = 4 \times 10^6$ K decreasing toward higher and lower values down to $T_c = (1\text{–}1.5) \times 10^6$ K, which correspond to the corona. The length of the loop along the line-of-sight is assumed to be of the order of the loop thickness Δh, i.e., approximately $(5\text{–}10) \times 10^8$ cm and the electron density within the layer is assumed to be $N \sim (10^9\text{–}10^{10})\ \mathrm{cm}^{-3}$.

Calculations show that the geometric thickness of an optically thick gyroresonance layer responsible for radiation at a frequency $f = 3f_B$ is much less than the transverse dimensions of the hot loop and its optical thickness is $\tau_3 \gg 1$ for both ordinary and extraordinary modes. In the range from $f_1 = 3f_{B_1}$ to $f_2 = 3f_{B_2}$ the brightness temperature at f must be equal to the plasma kinetic temperature at a height h_3 at which $f_B = f/3$:

$$T_b(f) = T(h_3) , \tag{2}$$

where the relationship between h_3 and f in the magnetic field model (1) follows from the condition

$$h_3 = b[(3f_{B_{ph}}/f)^{1/3} - 1] \tag{3}$$

($f_{B_{ph}} = eB_{ph}/2\pi mc$ is the gyrofrequency at the photospheric level). The frequency spectrum is expected to represent a line that repeats, in a sense, the temperature distribution in the coronal loop. The line width is determined by the magnetic field inhomogeneity along the line-of-sight in the loop. The distribution $T(h)$ across the coronal loop, reconstructed from the cyclotron line profile (the solid curve in Figure 1) is given in Figure 3 under the assumption that this line is the third cyclotron harmonic

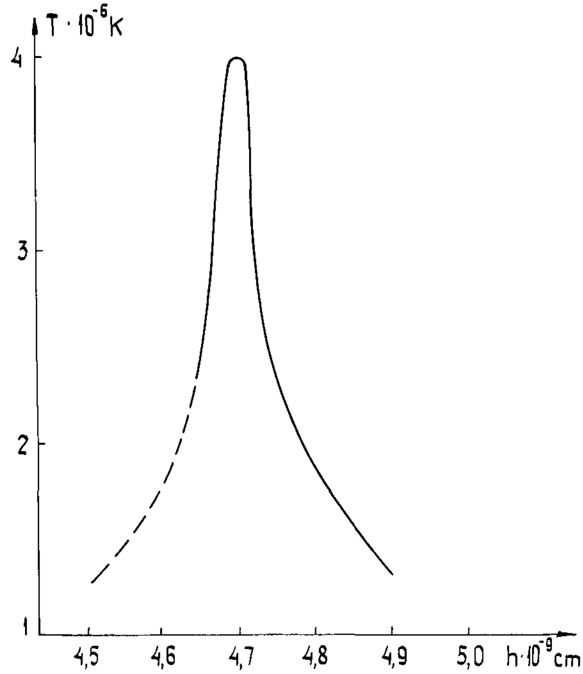

Fig. 3. Temperature distribution through a hot loop reconstructed from the observed cyclotron line profile (h is the height above the photosphere).

and the magnetic field varies with height as in expression (1). Since the assumption of optically thick gyroresonance layer $s = 3$ is valid when the plasma parameters range widely (for details see Zheleznyakov and Zlotnik, 1988), it should be natural to expect no polarization and relatively stable line characteristics for the two days of observation (the layers $s \geq 4$, radiation escaping the loop passes through in the corona, are too optically thin for extraordinary and ordinary modes to introduce a noticeable polarization).

Note that the relation between the observed line and other cyclotron harmonics is not so reliable. Indeed, the radiation in the cyclotron line at $s = 2$ passes through the layer $s = 3$ in the higher corona with a weaker magnetic field. Being optically thick for the extraordinary mode in a wide range of angles α between the magnetic field and the line-of-sight and optically thin for the ordinary mode, this layer can appreciably polarize the outgoing radiation (in contradiction to the observational data). The relationship between the observed line and the fourth harmonic is also hardly possible. The point is that at $N \sim 10^9$–$10^{10}\ \mathrm{cm}^{-3}$ the layer $f = 4f_B$ is optically thin in a wide range of angles α, the brightness temperature is much lower than the kinetic temperature and the radiation is polarized.

3. Homogeneous Magnetic Field Model

Taking into account the magnetic field inhomogeneity within the loop cross-section in our model permits one to explain the cyclotron line characteristics. Meanwhile the source with a homogeneous magnetic field considered by Willson does not provide such an opportunity. In his model the observed line width cannot be reconciled with the absence of noticeable polarization. According to Willson, the source has the optimal parameters: a depth $l = 10^8$ cm, a temperature $T = 3.8 \times 10^6$ K (at an ambient plasma temperature $T_c = 1.5 \times 10^6$ K), an electron density $N \sim 10^9$ cm^3 and a magnetic field $B = 145$ G or 119 G (in those fields the fourth and the fifth harmonics, respectively, yield a cyclotron line frequency 1650 MHz). The line calculated by Willson for $f = 4f_B$ and $\alpha = 70°$ is similar to the solid line in Figure 1. Our calculations show that the radiation of a homogeneous plasma layer with the above parameters has a different spectrum shown by a dashed line in Figure 1. That the observed cyclotron line would not be explained by the homogeneous source model is demonstrated by the dependence (calculated for the above parameters) of the brightness temperature T_b, the polarization degree ρ at the line centre (at $f = 4f_B = 1658$ MHz) and the relative line width $\Delta f/f \approx 2\sqrt{2}\,\beta_T \cos\alpha$ ($\beta_T = (\kappa T/mc^2)^{1/2}$; κ is a Boltzmann constant) on the angle α in Figure 4. It is assumed that the background is due to unpolarized coronal radiation with a brightness temperature $T_c = 1.5 \times 10^6$ K. The observed parameters of the cyclotron

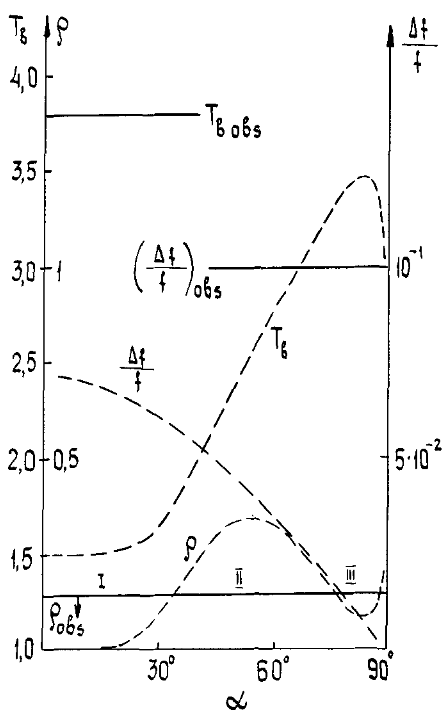

Fig. 4. Dependence of brightness temperature T_b, polarization degree ρ and line width $\Delta f/f$ on angle α in the homogeneous model.

line are also indicated. The angles α can be divided into three intervals, those of small (I), middle (II), and large (III) angles. In the first interval the line width is closest to the observed one and the polarization degree is below 15%, in accord with the observations. Meanwhile this line becomes very weak and indistinguishable against the coronal radiation background ($T_b \approx T_c$). The second interval is inadequate because of the high degree of polarization ($\rho > 15\%$), the relative weakness of the line ($T_b < 3 \times 10^6$ K) and the reduced line width ($\Delta f/f < 5 \times 10^{-2}$). Finally, the third interval conforms with the polarizational observations and ensures a reasonable temperature at the line centre but does not explain the observed line width (in the theory the line is too narrow (see Figure 2)).

Strong dependence of the line characteristics on the angle α in the optically thin source does not make it possible to explain their constancy for two days of observation. For this time the angle α changed, due to the Sun's rotation, by approximately 10°. If the angle α changed from 70° (the value adopted by Willson) to 80°, then $\cos\alpha$ changed by almost a factor of two. In the model of a homogeneous source it should be natural to expect a two-fold variation of the Doppler line width, which, however, was not observed.

4. Conclusion

The proposed scheme of cyclotron line formation in an inhomogeneous optically thick source, a flux tube filled with hot electrons (a hot coronal loop) explains the observed properties of the line recorded by Willson (1985) such as its nearly stable maximum brightness temperature, profile and width, and low degree of polarization.

An investigation of cyclotron lines in the microwave spectrum is an effective tool for magnetic field and plasma diagnostics in solar active regions. It permits one to ascertain the parameters of the magnetic field and of the hot plasma in the magnetic flux tube above the bipolar group of spots. The magnetic field at the loop axis can be found from the relation $f_B = f_{\max}/3$, where $f_{\max}$ is the frequency at the line centre. The kinetic temperature at the loop axis is equal to the brightness temperature at the line centre of the harmonic number s. The magnetic field inhomogeneity across the loop is determined by the line width: $\Delta B/B \sim \Delta f/f$. The dependence of the kinetic temperature on the magnetic field (or its distribution in the loop along the line-of-sight in the given model of magnetic field in the active corona is reconstructed from the line profile).

Since the line recorded by Willson (1985) probably refers to the third cyclotron harmonic, it appears in the region where the magnetic field is 196 G (to an accuracy of 2%, determined by the distance between the neighboring frequency channels) and where there is a hot loop with an axial temperature $T = 4 \times 10^6$ K and a temperature distribution similar to that shown in Figure 3.

Further progress in the study of cyclotron lines in the solar microwave spectrum would require spectral and polarization measurements at multiple frequencies corresponding to harmonics $s = 2, 3, 4$ (at VLA, for example, in the ranges 1100 MHz and 2200 MHz together with the operative range 1650 MHz). Detection of cyclotron features in these ranges will fully exclude the uncertainty in choosing the observed harmonic number and will permit reliable diagnostics of the physical parameters of the coronal plasma based on cyclotron lines.

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