THERMAL CYCLOTRON RADIATION FROM SOLAR ACTIVE REGIONS

V.V.Zheleznyakov, E.Ya.Zlotnik
Institute of Applied Physics, Academy of Sciences,
Gorky, USSR

Various frequency spectra with the fine structure resulting from the thermal cyclotron radio emission from solar active regions are discussed. The conditions in sources (distribution of magnetic field and kinetic temperature over the height) are put forward which provide the frequency spectrum as a set of cyclotron lines and high frequency cut-offs. For each kind of distribution the frequency spectrum and polarization are of peculiar character. This permits one to find the conditions in the source through the properties of the observed microwave solar radio emission. To obtain reliable data on the fine structure and judge about conditions in the sources it is necessary to study microwave solar radio emission using the swept-frequency or multi-channel receivers combined with high directional antennae.

1. All the phenomena in microwave solar radio emission occur against the S-component - slowly varying radiation of the local sources above sunspots and flocculi in the active regions of the corona and chromosphere. The S-component is characterized by a smooth frequency spectrum with the maxima in the wavelength range $\lambda \sim 5 - 10$ cm, the absence of polarization at longer wavelengths and the polarized radiation at shorter wavelengths (the sense of polarization favours the extraordinary wave). These peculiarities were explained in terms of thermal cyclotron and free-free radiation mechanisms by Zheleznyakov (1962, 1963) and Kakinuma and Swarup (1962). Further progress in the theory of the S-component was made by analyzing various models of active regions, calculating the expected characteristics of cyclotron (and free-free) radio emission in these models, and comparing the obtained characteristics with the observed ones (see Pikel'ner et al., 1966, Zlotnik, 1968, Lantos, 1968). However, recently Zheleznyakov and Zlotnik (1979a, 1980) paid at-

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tention to the fact that thermal cyclotron radio emission in neutral current sheets of the corona represents a set of discrete cyclotron lines. If the kinetic temperature of a plasma in the sheets is sufficiently great ($T \sim 10^7 - 10^8$ °K) these lines may be recorded against the S-component mostly in the radiation of the second and the third harmonics of the electron gyrofrequency $\omega_B = eB/mc$. The fine structure such as cyclotron lines should be expected in the pre-flare phases of active regions developing when the formation of hot neutral current sheets is most probable. This possibility of appearance of narrow-band features in the frequency spectrum of microwave radio emission and the cases of recording cut-offs and narrow-band features in the spectrum of radio emission of solar local sources (Kaverin et al., 1976) stimulated the authors of the report to consider more thoroughly the other variants of the fine structure origin. The results of the performed analysis are given below.

2. Before discussing different variants of appearance of the fine structure in the microwave solar radio spectrum, let us recall the peculiarities of the cyclotron mechanism in the inhomogeneous magnetic fields above sunspots and the conditions of generation of the typical S-component (see in more detail Zheleznyakov, 1970, § 29 and 1977, § 13).

The non-relativistic electrons in a magnetic field are known to radiate and absorb the electromagnetic waves at the frequencies equal or multiple to the gyrofrequency: $\omega \approx s\omega_B$, where s = 1, 2, 3... is the number of cyclotron harmonic. Therefore cyclotron radiation and wave absorption at a given frequency in the inhomogeneous magnetic field occur in the gyroresonance layers where the gyrofrequency

$$\omega_B \approx \omega / s . \qquad (1)$$

Under the typical conditions of the solar corona and chromosphere the optical thickness of these layers τ is different for the ordinary and the extraordinary waves. For the ordinary waves the optically thick layers ($\tau > 1$) correspond to the harmonics $s \leq 2$; for the extraordinary waves such layers correspond to the values $s \leq 3$. In both cases the gyroresonance layers are optically thin ($\tau \ll 1$) for the higher harmonics.

A theory of the S-component is based on a model of the active region above a sunspot represented in Fig.1a. According to this figure[1], the gyrofrequency ω_B (in a magnetic field B) decreases monotonically with the height h

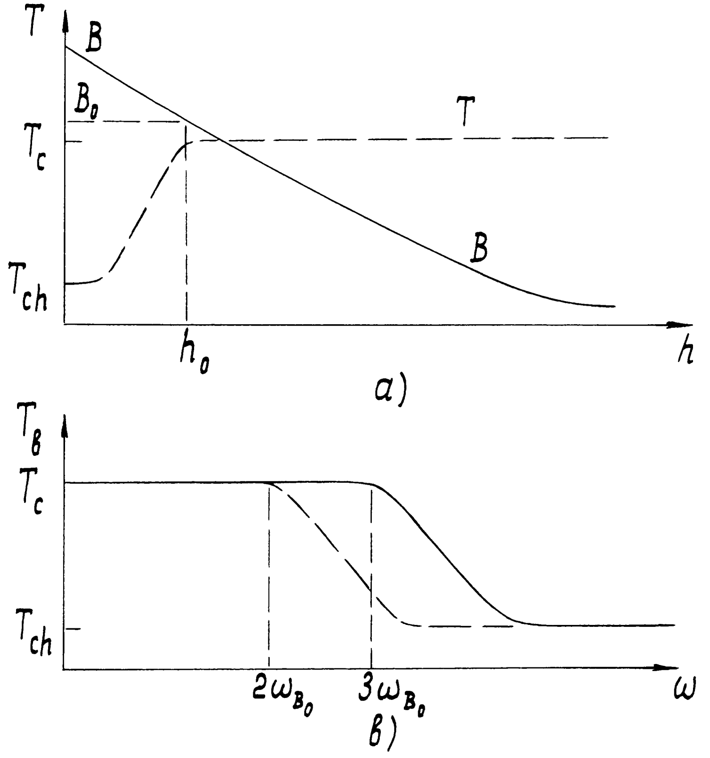

Figure 1. The model of a standard source of the S-component: a) distribution of the magnetic field B and the kinetic temperature T over the height h (h_0 is the lower edge of the corona, B_0 is the magnetic field at this level); b) the frequency spectrum of radiation; solid and dashed lines here and elsewhere correspond to extraordinary and ordinary waves.

over the photosphere. The kinetic temperature of a plasma increases from the chromospheric values ($T_{ch} \sim 10^4 - 3\times10^4$ °K) to those typical of the active corona ($T_c \simeq 3\times10^6$ °K). In such magnetic fields the gyroresonance layers (1) corresponding to the higher harmonics are situated at greater heights in the solar atmosphere (closer to the observer). This fact alongside with the above values of optical thickness for the ordinary and extraordinary waves of gyroresonance layers permit us to conclude that the second gyroresonance layer radiates the ordinary waves and the third gyroresonance layer radiates the extraordinary ones. The brightness temperature of the ordinary component of radiation

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$$T_b \approx T(h_2), \qquad (2)$$

where h_2 is the height of the second gyroresonance layer with the gyrofrequency $\omega_B = \omega/2$; the brightness temperature of the extraordinary mode

$$T_b \approx T(h_3), \qquad (3)$$

where h_3 is the height of the third gyroresonance layer $\omega_B \doteq \omega/3$ (see formula (1)). Radiation from the deeper layers is absorbed at the heights h_2 and h_3 , respectively. The contribution of the optically thin higher harmonics is insignificant. The said above is sufficient to build a frequency spectrum of the S-component representing the dependence $T_b(\omega)$ for both waves. Such a dependence is given in fig.1b. From this figure it is clear that for the extraordinary radiation $T_b=T_c$ at the frequencies $\omega < 3\omega_{B_0}$ corresponding to the localization of the third gyroresonance level in the corona - at the heights $h > h_0$ At higher frequencies the level S=3 sinks to the chromosphere. In the transient region T_b drops tending to the value T_{ch}. The same is observed for the ordinary mode but the drop in T_b begins earlier - at the frequency corresponding to the moment of the transition of the level S=2 to the heights $h < h_0$. From Fig.1b it follows that the thermal cyclotron radiation in a standard model of the S-component is unpolarized at the low ($\omega < 2\omega_{B_0}$) and the higher ($\omega > 3\omega_{B_0}$) frequencies and is rather strongly polarized in the range of the intermediate frequencies $2\omega_{B_0} < \omega < 3\omega_{B_0}$ for which one of the gyroresonance layers S=2,3 or both of them are localized in the transient region from the chromosphere to the corona having a strong temperature gradient.

It should be noted that in the present report all the frequency spectra are represented in terms of $T_b(\omega)$ rather than of the specific intensity $I(\omega)$. To transform $T_b(\omega)$ into dependence of I on ω one should taken into account that $I \propto \omega^2 T_B$. As a result we obtain that the spectrum $I_e(\omega)$ has a maximum at the frequency $\omega_{max} \approx 3\omega_{B_0}$ and the spectrum of the ordinary radiation of the S-component has a maximum at the frequency $\omega_{max} \approx 2\omega_{B_0}$.

The given character of the frequency spectrum and polarization of the S-component is well confirmed by observations of the microwave radio emission of solar local sources during many years (Gelfreigh et al., 1970). It is clear, however, that the model considered does not exhaust all

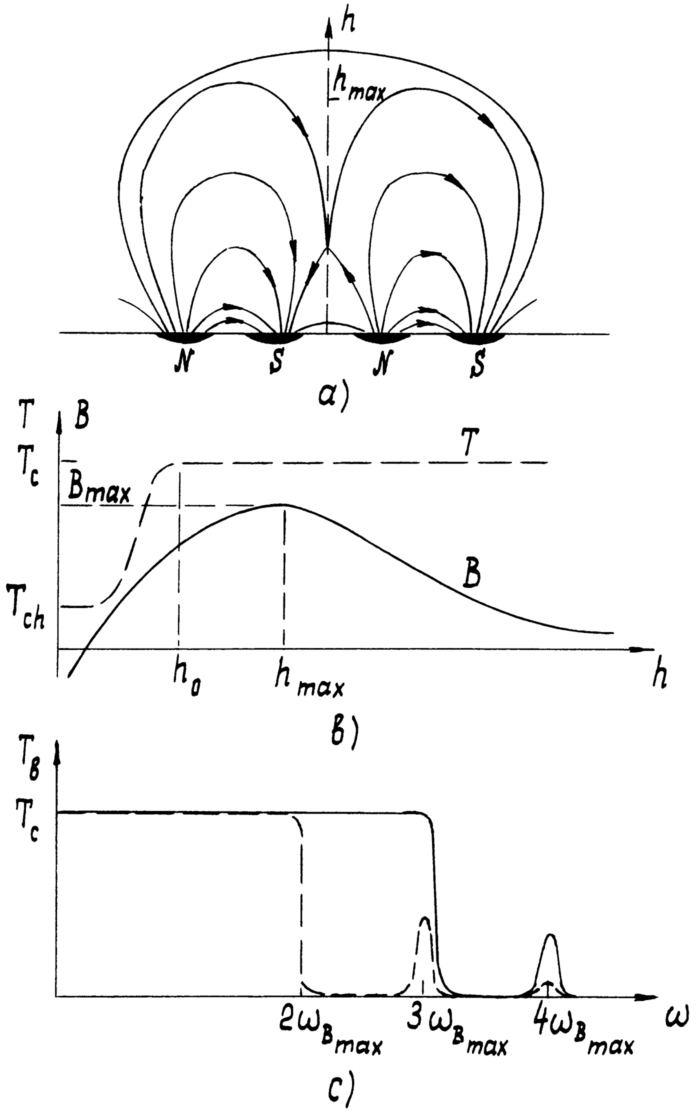

Figure 2. The model of a source with the maximum of the magnetic field over height: a) magnetic lines of force above a group of sunspots (h_{max} is the height at which the magnetic field has its maximum value); b) distribution of the magnetic field and kinetic temperature over the height; c) the frequency spectrum of radiation.

the variety of conditions in the active regions. Consequently, the frequency spectra of radio emission may be by far more complicated.

3. Let us consider a frequency spectrum of thermal cyclotron radiation in a model where the value of the magnetic field reaches its maximum at a certain height h_{max} for the previous distribution of temperature (see Fig. 2b). Such a distribution of the magnetic field can be realized, for example, in a group of sunspots represented in Fig.2a even disregarding the electric currents in the coronal and the chromospheric plasma (Sweet, 1968). Here along the axis h passing through the neutral (zero) line of the magnetic field, the maximum B is certainly present. If $h_{max} > h_0$ where h_0 is the lower edge of the corona, then the considered model is in fact reduced to the standard model in Fig.1a. But if $h_{max} < h_0$, then the radiation spectrum changes significantly its form compared to the usual spectrum of the S-component. In fact, as implied by Fig.2c, the brightness temperature drops toward the higher frequencies at the points $\omega = 2\omega_{B_{max}}$ (the ordinary waves) and $\omega = 3\omega_{B_{max}}$ (the extraordinary waves), since along the axis h the magnetic fields have no values exceeding B_{max}. Note that such values may exist at small heights in the chromosphere below the neutral point. In this case, however, the kinetic temperature is low; thus, contribution of these regions to radiation is neglected. In the frequency range $2\omega_{B_{max}} < \omega < 3\omega_{B_{max}}$ the radio emission is strongly polarized (with an excess of the extraordinary wave). The degree of polarization approximates 100%. Moreover, it is important to note that at the frequencies $3\omega_{B_{max}}, 4\omega_{B_{max}}, \dots$ the cyclotron lines emerge originating from the significant growth of the optical thickness of gyroresonance layers due to a small change in the magnetic field at the heights $h \sim h_{max}$. For the optically thin gyroresonance layers the growth of the optical thickness leads to the corresponding increase in the brightness temperature at the frequencies $\omega \approx s\omega_{B_{max}}$. The radiation in the line $\omega \approx 3\omega_{B_{max}}$ consists only of the ordinary waves. The lines at the higher harmonics are partly polarized with an excess of the extraordinary waves.

The distinctive feature of the model in Fig.2b with the magnetic field maximum at a certain height in the corona is the fact that the fine structure in the frequency spectrum (a set of cyclotron lines and high-frequency cut--offs) appear under the condition that the sharp gradients of the magnetic field and electron density are absent in the corona and chromosphere.

The calculated profiles of the cyclotron lines and high-frequency cut-offs are represented in Fig.3 (for the parabolic approximation of the dependence $B(h)$ near the maximum of the magnetic field).

At the harmonics s for which the optical thickness is small at the frequency $\omega = 3\omega_{B_{max}}$, we obtain a line the form of which is represented by the curve a) in Fig.3. The

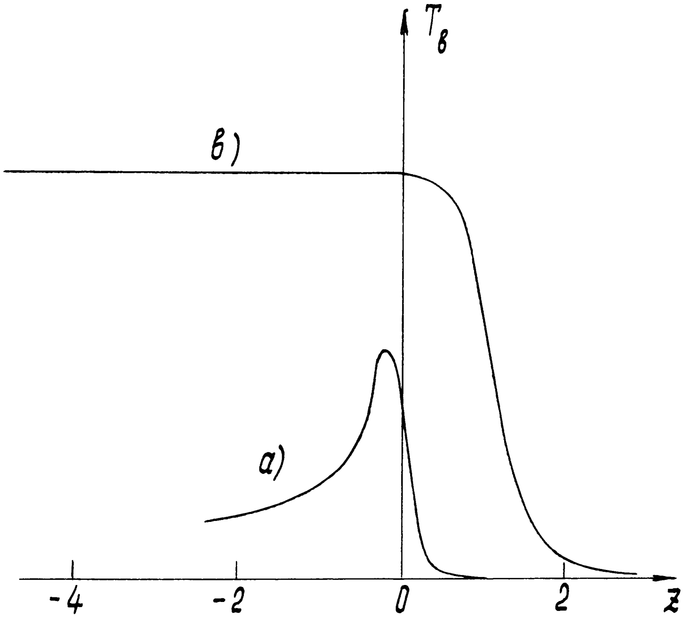

Figure 3. The calculated dependence T_b in the cyclotron line (a) and in the high-frequency cut-off (b) on the parameter z in the model with the maximum of the magnetic field (Fig.2a).

halfwidth of the line $\Delta\omega$ is determined by the Doppler effect:

$$\frac{\Delta\omega}{\omega} \approx \sqrt{2}\,\beta_T \cos\alpha\,, \tag{4}$$

where $\beta_T = v_T/c$, v_T is the thermal electron velocity, α is the angle between the magnetic lines of force and the line of sight.

In case the optical thickness at these frequencies is well above unity, the frequency spectrum takes the form of a high-frequency cut-off given by the curve b) in Fig.3. The characteristic width of the cut-off $\Delta\omega$ is as previously determined by relation (4).

4. Judging by the X-ray emission data (Cheng, 1977) it is fairly possible for the force tube of a bipolar magnetic field above sunspot to be filled by hot electrons (Fig.4a). These electrons may, in principle, fill the whole of the tube or be present as an admixture to the electron

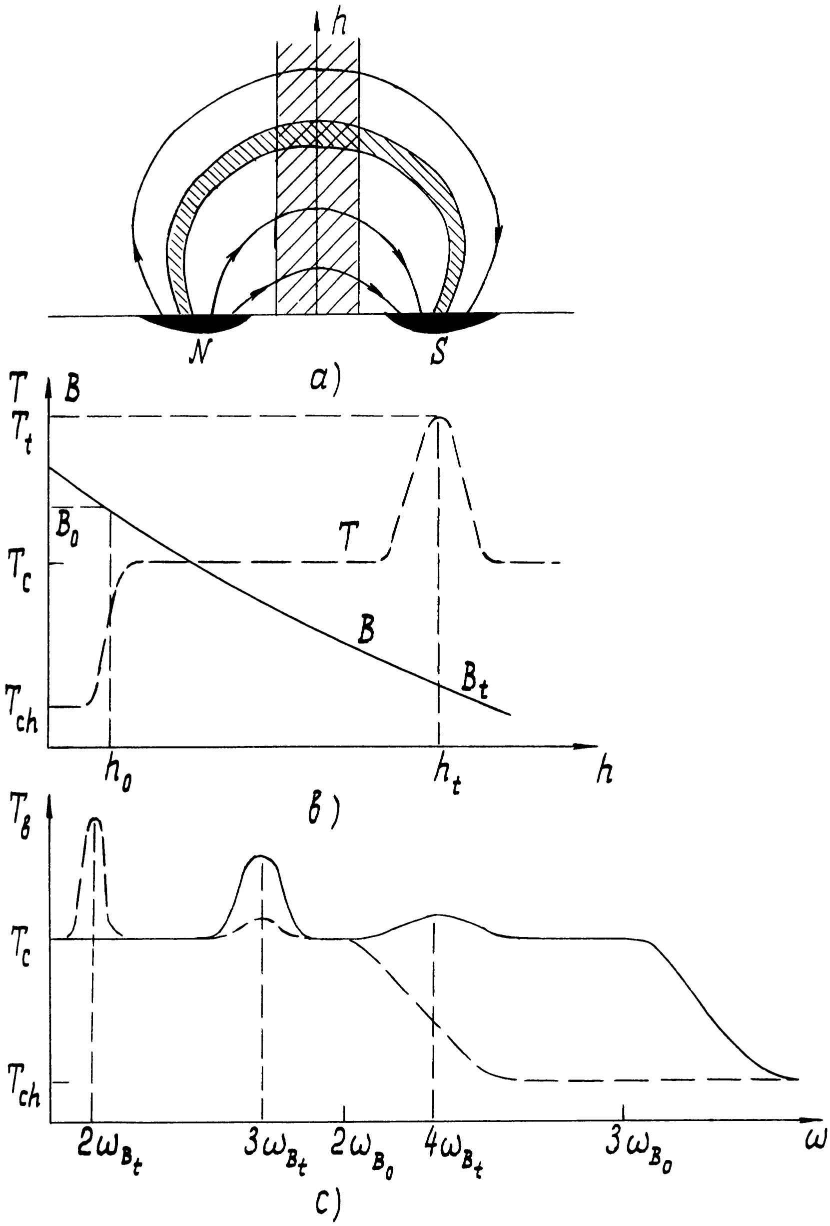

Figure 4. The model of a source with hot electrons filling the magnetic field force tube: a) magnetic lines of force with hot electrons (small hatching) and those crossed by the antenna pattern (large hatching); b) distribution of the magnetic field and temperature over the height (B_t is the magnetic field at the level h_t of the force tube); c) the frequency spectrum of radiation.

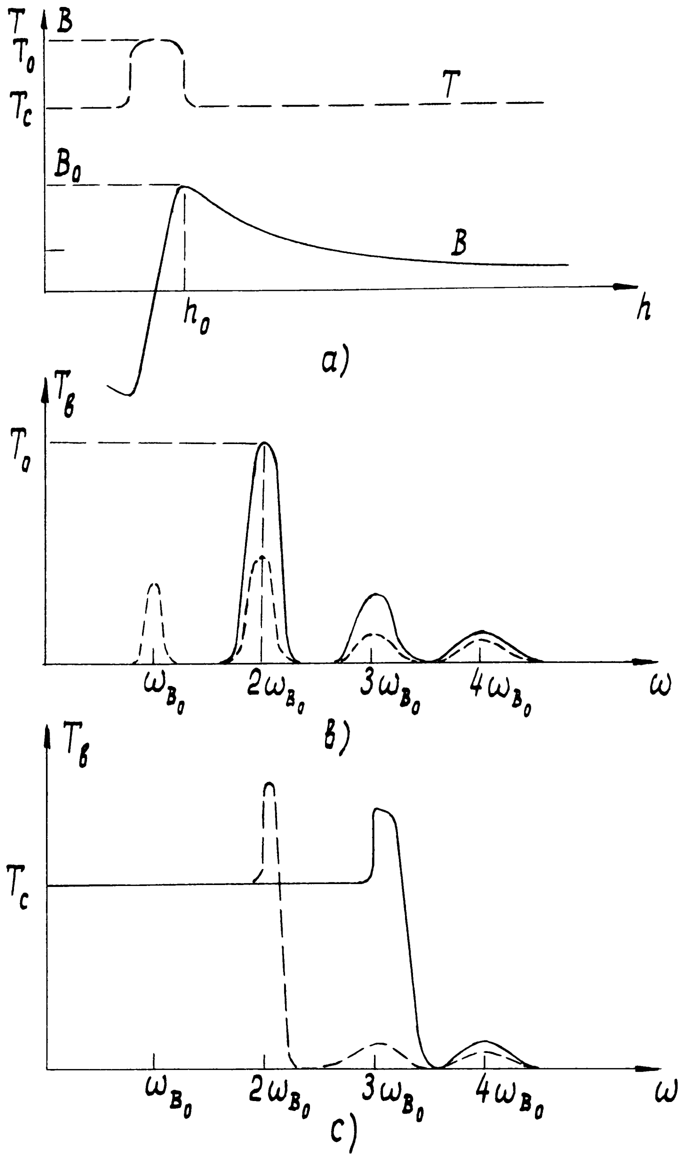

Figure 5. The model of a source with a neutral current sheet and a monotonically vanishing magnetic field: a) distribution of the magnetic field and kinetic temperature over the height (h_0 is the conventional edge of the neutral current sheet); b) the frequency spectrum of the proper radiation of the neutral current sheet; c) the frequency spectrum with allowance for absorption and radiation in the corona.

component having a usual coronal temperature.

As example we treat the case where a relatively thin force tube is filled by hot electrons (with $T \gg T_c$). Let us also assume that their pressure is small compared with the magnetic pressure and, therefore, the pressure of hot electrons does not markedly change the value of a magnetic field in the tube. The discussed distribution of T and B along the axis h is shown in Fig.4b.

It is easy to see that in the framework of this model the frequency spectrum of cyclotron radiation escaping the corona along the axis h will represent a superposition of the usual spectrum of the S-component (Fig.1b) and cyclotron lines at the frequencies multiple to ω_{B_t} (ω_{B_t} is the gyrofrequency in a force tube at the height h_t). This spectrum is given in Fig.5b. Analysis shows that the force tube can radiate only the cyclotron lines $\omega \approx 2\omega_{B_t}, 3\omega_{B_t}, \ldots$. The second line is totally polarized in the sense of the ordinary wave. The lines beginning with the third are partly polarized, with an excess of the extraordinary wave.

5. It has been mentioned at the beginning of the report that the fine structure of a frequency spectrum may be due to the cyclotron radiation of hot neutral current sheets (Zheleznyakov and Zlotnik, 1979 a). These, in all probability, appear in the lower corona or in the upper chromosphere during the pre-flare phase of solar activity. Thus, detection of the spectral fine structure associated with neutral current sheets may prove to be an important method of predicting and recognizing such sheets.

The distribution of the magnetic field and temperature in the corona along the line of sight passing through a neutral current sheet is given in Fig.5a. It is assumed here that the plasma has an enhanced temperature only within the limits of the neutral current sheet including the edge regions with a magnetic field $B < B_0$.

The frequency spectrum of thermal cyclotron radiation from a neutral current sheet approaching the point h_0 is seen in Fig.5b. It represents a set of rather broad lines at the harmonics of the gyrofrequency $\omega = s\omega_{B_0}$. The calculation of such a spectrum has been discussed in ample detail by Zheleznyakov and Zlotnik, 1980; so it is omitted here. Note only that the appearance of discrete cyclotron lines is due to the generation of radiation in the region of a quasi-uniform magnetic field B_0 at the edge of the neutral sheet. The source is restricted from below by the level at which the plasma frequency ω_p is equal to the harmonic frequency. It should be readily apparent that the given level in the nonrelativistic plasma must be localized far from the middle (at the edge) of the sheet. In fact, from the condition of static equilibrium of a plasma in the magnetic field of a neutral sheet $B_0^2/8\pi = 2N_0 \varkappa T$ it follows that $\omega_{p_0} = \omega_{B_0}/2\beta_T$ (N_0 and ω_{p_0} are the density and the plasma frequency in the middle of the sheet). Since the parameter $\beta_T \ll 1$, the last equality implies that $\omega_{p_0} \gg \omega_{B_0}$. At low harmonics of the gyrofrequency $\omega = S\omega_B$ this inequality ensures the validity of the condition $\omega_p \gg \omega$. Hence it is evident that the plasma level $\omega_p = \omega$ for the emitted frequencies is located far from the middle of the sheet in the region where the magnetic field is close to B_0 .

When escaping a neutral current sheet the cyclotron radiation does not contain the extraordinary mode at the frequency $\omega = \omega_{B_0}$ since $n_e^2 < 0$ in the sheet. The lines $\omega = 2\omega_{B_0}, 3\omega_{B_0}, \ldots$ are unpolarized or partly polarized with an excess of the extraordinary wave depending on whether the source is optically thick or optically thin. The spectrum and the polarization of radiation escaping the corona certainly differ from those in Fig.5b due to absorption of the neutral current radiation in the upper regions of the corona and of the proper cyclotron radiation of these regions. For example, the line $\omega = \omega_{B_0}$ in the ordinary radiation and the extraordinary mode in the line $\omega = 2\omega_{B_0}$ will vanish due to absorption in the corona (the first will vanish at the gyroresonance layers $\omega = 2\omega_B$, the second - at the level $\omega = 3\omega_B$). In general the observed spectrum takes the form presented schematically in Fig.5c. The high-frequency cut-offs at the frequencies $\omega = 2\omega_{B_0}$ and $\omega = 3\omega_{B_0}$ are associated with the limiting from below of the source of the S-component in the corona: the radiation from the deeper regions of the corona below the neutral current sheet does not penetrate through the sheet at the frequencies $\omega < \omega_p$ (on the emission propagating through neutral current sheets in the solar corona see Zheleznyakov and Zlotnik, 1979b).

Let us stress once again that thermal cyclotron radiation is produced in the neutral current sheet by only the external regions of the sheet. Further behaviour of the magnetic field toward the deeper layers(drop to zero and reversal of sign or reducing to a certain limiting value followed again by increasing) does not affect the formation of the frequency spectrum as a set of resolved cyclotron lines. Therefore the radiation with the characteristics shown in Fig.5c may, in principle, be generated by the hot electrons trapped by the local minimum of the magnetic field in a force tube. This minimum may occur in a force tube if the energy density of hot electrons is comparable with that of the magnetic field.

6. All the considered variants of the magnetic field and electron density distributions over the height in the

solar atmosphere differ from the standard model of the S-component. They result in the frequency spectrum with the fine structure in the form of cyclotron lines and high-frequency cut-offs. Every model however has a peculiar character of the spectrum and polarization of thermal cyclotron radiation. The last circumstance permits us to judge on the specific type of the dependence $N(h)$ and $T(h)$ by the observed spectrum and the polarization of microwave radiation from solar active regions. From the said above it is clear that for the detection of cyclotron lines and the study of fine structure, the simultaneous spectral and polarization measurements in the wide frequency range (covering at least a factor of three in frequency) and with the adequate resolution $\Delta\omega/\omega \leq 0.05$ are necessary. The spectrographs should be combined with the antenna systems ensuring the directivity as high as possible: antenna pattern width must be less than a sunspot or the distance between sunspots in a group. The antennae of the type RATAN-600 and the 100m Bonn radiotelescope are preferable here since, in general, when receiving the radiation from the whole active region the fine structure is smoothed and one hardly can detect with confidence the cyclotron lines and cut-offs. In this case their identification and interpretation become doubtful. An example of this effect is given by the radiation from a magnetic force tube (see Fig.4). If the trapped hot electrons are dissipated along the tube over the region where the magnetic field varies greatly ($\Delta B/B \gtrsim 1$), then in the total radiation the cyclotron lines will diffuse and the frequency spectrum will be smoothed. Conversely, if the receiving is performed by the antenna with narrow knife or pencil directivity pattern (the cross-section of this pattern is represented in Fig.4a), then the frequency spectrum of the observed cyclotron radiation will contain discrete cyclotron lines.

A detailed discussion of the problems tackled in the present report is offered in papers by Zheleznyakov and Zlotnik, 1979a, 1980)

Conclusion

For many years the microwave solar radio emission was investigated, as a rule, basing on the measurements of the flux and the polarization at some well spaced frequencies. As implied by the given report, some valuable information on the cyclotron lines and cut-offs in the frequency spectrum of local sources has been omitted. These peculiarities of the spectrum may suggest some valuable data on the magnetic fields and the temperature in solar active regions. To do this, it is necessary, however, to change a method of observations and pass to the study of microwave solar radio emission using the spectrographs and spectropolarimeters combined with highly directional antennae.

1) This plot and subsequent ones in our report (except for Fig.3) are only outlined.

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