# ON POSSIBLE ESCAPE OF ELECTRON CYCLOTRON MASER RADIATION FROM ACTIVE REGIONS IN THE SOLAR CORONA

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**Abstract**

An important handicap to considering the electron-cyclotron maser (ECM) mechanism as a source of intense radio emission from solar active regions is strong absorption of this radiation in the upper layers where the gyrofrequency harmonics satisfy the cyclotron resonance condition. The cyclotron absorption markedly suppresses the efficiency of ECM radiation in a wide angle between the direction of propagation and the magnetic field. Weak absorption is possible only in a narrow angle "window" along (for ordinary and extraordinary modes) and across (for ordinary mode) magnetic field. However, ECM radiation escaping the sources does not get into these "windows of transparency" due to specific kinematic conditions corresponding to coronal magnetic traps. This work is devoted to a study of the induced scattering of ECM radiation by equilibrium ions in the source. It is shown that under definite conditions the induced scattering results in formation of a condensed spectrum of ECM radiation with wave vectors almost along the magnetic field. This allows the radiation to escape from the source through the window of transparency. The most favorable conditions are realized for the ordinary mode. The optical depth of the ECM radiation relative to the scattering process, as well as the angle width of the condensed spectrum for the ordinary and extraordinary waves, are estimated in conformity to the sources of type I noise storms in the solar corona. It is shown that in this case the escaping radiation is polarized in the ordinary mode.

## 1 Introduction

Two mechanisms for generation of the powerful, sporadic radio emission emerging from the corona are usually considered: (i) the generation of plasma waves by nonequilibrium populations of fast electrons, with subsequent transformation into electromagnetic radiation, and (ii) the electron-cyclotron maser (ECM) mechanism, which involves the direct

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generation of electromagnetic radiation by nonequilibrium electrons. The plasma mechanism as applied to solar radio emission has been studied in detail in [Zheleznyakov and Zaitsev, 1970a,b; Stepanov 1973] and a number of other works. The ECM mechanism is considered to be more efficient, since it assumes the direct amplification of electromagnetic waves at the gyrofrequency harmonics, and can be realized for electrons with both anisotropic and isotropic velocity distributions [Kuckes and Sudan, 1971; Stepanov, 1978; Aschwanden, 1990]. The main problem with using the ECM mechanism to explain solar radio emission with high brightness temperatures is the expected strong absorption of the ECM radiation in the higher-lying layers of the corona, where the cyclotron-resonance condition at the harmonics of the electron gyrofrequency $\omega_{\rm Be}$ is satisfied. Estimates of the optical depth to gyroresonance absorption for radiation at 100 MHz propagating through the solar corona indicate that the ECM radiation leaving the solar corona should be attenuated by a factor of $\sim \exp(10^4)$ for the extraordinary wave and by a factor of $\sim \exp(10^3)$ for the ordinary wave. At the same time, there exists a "window" for the ECM radiation with a width of several degrees along the magnetic field, through which this radiation can escape without being absorbed. In the case of the ordinary wave, there is also a window at an angle near $\pi/2$, also with a width of several degrees [Stepanov et al., 2001].

This raises the question of whether these windows could serve as channels for the escape of ECM radiation from solar corona. This would require that an appreciable fraction of the generated radiation be scattered within the source, such that it is concentrated near a window of transparency. This scattering must be induced, since only then is it possible to accumulate the optical depth required to transform the angular spectrum of the radiation. An induced nature for the scattering is also suggested by the relatively high intensities of the radiation arising during solar flares.

We study here the induced scattering of ECM radiation on thermal particles in the main plasma, and demonstrate the possibility of forming condensates in the angular spectrum of the radiation near a window of transparency, enabling the escape of the ECM radiation from the source without appreciable cyclotron absorption.

## 2 Basic equations

As a rule, the radio emission of solar and stellar flares arises in coronal magnetic traps. When fast electrons are injected into a trap, a nonequilibrium particle distribution with an anisotropic velocity distribution transverse to the magnetic field rapidly forms. This anisotropy is associated with the presence of a loss cone in the trap, which causes energetic electrons with small transverse velocities to enter the loss cone and thermalize as a result of collisions with particles of the main plasma at the footpoints of the trap. This gives rise to an excess of energetic electrons with high transverse velocities in the trap. Under appropriate conditions, the resulting transverse-velocity anisotropy brings about the direct amplification of electromagnetic waves due to the development of the ECM instability [Aschwanden, 1990]. The ECM instability has been studied for various types of fast-particle distribution functions with a loss cone for a wide range of temperatures for the main plasma, $T = 10^6 - 10^7$ K, and various ratios $\omega_{\rm Pe}/\omega_{\rm Be} = 0.1 - 1.4$ ($\omega_{\rm Pe}$ is the plasma frequency). If the magnetic field is sufficiently strong ( $\omega_{\rm Pe}/\omega_{\rm Be} = 0.24 - 0.4$), the ECM generates predominantly extraordinary waves at the first harmonic of the gyrofrequency (more precisely, at a frequency slightly higher than $\omega_{\rm Be}$). In the interval of parameters $0.24 - 0.4 < \omega_{\rm Pe}/\omega_{\rm Be} < 1$, ordinary waves are generated at the first harmonic of the gyrofrequency. In both cases, the maximum increment is realized for waves propagating at an angle of $\theta_{\rm m} \simeq 70°$ to the magnetic field. The angular width of the spectrum of the excited waves is $\Delta\theta \simeq 3°$. When $\omega_{\rm Pe}/\omega_{\rm Be} > 1$, the maximum increments occur for plasma waves at the upper hybrid frequency, $\omega \simeq \sqrt{\omega_{\rm Pe}^2 + \omega_{\rm Be}^2}$ while ECM radiation in the form of extraordinary waves at the frequency $\omega \simeq \omega_{\rm Be}$ has an increment that is several orders of magnitude smaller, and does not contribute significantly to the flux of radio emission from the traps.

The high power of the radiation emitted by active regions on the Sun and the relatively small size of the corresponding sources suggest that induced scattering processes may dominate, and that the source may have a high optical depth to these processes. Under these conditions, the radiative-transfer equation describing induced scattering can be written

$$\frac{\partial W_\sigma(\vec{k})}{\partial t} = W_\sigma(\vec{k}) \int G_{\sigma\sigma'}(\vec{k}\vec{k}')W_{\sigma'}(\vec{k}')d\vec{k}', \tag{1}$$

where $G_{\sigma\sigma'}(\vec{k},\vec{k}')$ is the coefficient for scattering a wave $\sigma'$ with wave vector $\vec{k}'$, frequency $\omega'$, and spectral density $W_{\sigma'}(\vec{k}')$ into a wave $\sigma$ with wave vector $\vec{k}$, frequency $\omega$, and spectral density $W_\sigma(\vec{k})$. In the case where the main contribution to the scattering is given by ions, i.e., where

$$Z_{\rm i} \equiv \frac{\omega - \omega'}{\sqrt{2}|\vec{k}-\vec{k}'|v_{\rm Ti}} \leq 1 \quad \text{and} \quad Z_{\rm e} \equiv \frac{\omega - \omega'}{\sqrt{2}|\vec{k}-\vec{k}'|v_{\rm Te}} \ll 1, \tag{2}$$

the coefficient for scattering is described by the expression

$$G_{\sigma\sigma'}(\vec{k},\vec{k}') = \frac{8\pi e^2}{m_{\rm e}^2\omega\omega'}\frac{\sqrt{\pi}\omega_{\rm Pi}^2}{v_{\rm Ti}^2}\left(1+\frac{T_{\rm e}}{T_{\rm i}}\right)^{-2}\Psi_{\sigma\sigma'}(\theta,\theta')Z_{\rm i}e^{-Z_{\rm i}^2}, \tag{3}$$

where $\Psi_{\sigma\sigma'}(\theta,\theta')$ is a function determining the angular pattern of the induced scattering [Zaitsev at al., 2005], $\omega_{\rm Pi}$ is the ion plasma frequency, $T_\alpha$ and $v_{{\rm T}\alpha}$ are, correspondingly, the temperature and the thermal velocity of the spicies $\alpha$ of the plasma, $\alpha = e, i$ . If $Z_{\rm i} \gg 1$ and $Z_{\rm e} \leq 1$, then the main contribution to the scattering is given by electrons, and [Zaitsev at al., 2005]

$$G_{\sigma\sigma'}(\vec{k},\vec{k}') = \frac{8\pi e^2}{m_{\rm e}^2\omega\omega'}\frac{\sqrt{\pi}\kappa^4 v_{\rm Te}^2}{\omega_{\rm Pe}^2}\Psi_{\sigma\sigma'}(\theta,\theta')Z_{\rm e}e^{-Z_{\rm e}^2}. \tag{4}$$

Equations (3) and (4) are valid for scattering by nonmagnetized particles where the condition $\dfrac{\kappa_\perp v_{{\rm T}\alpha}}{\omega_{{\rm B}\alpha}} \gg 1$ is fulfilled [Zheleznyakov, 1995]. Here $\kappa_\perp$ is the component of the difference vector $\vec{\kappa} = \vec{k} - \vec{k}'$ perpendicular to the magnetic field. In the case of scattering by magnetized particles, $\dfrac{\kappa_\perp v_{{\rm T}\alpha}}{\omega_{{\rm B}\alpha}} \leq 1$, the expression $Z_\alpha = \dfrac{\Omega}{\sqrt{2}\kappa v_{{\rm T}\alpha}}$ in Eqs.(3) and (4) must be replaced by $Z_\alpha = \dfrac{\Omega}{\sqrt{2}\kappa_\parallel v_{{\rm T}\alpha}}$, where $\kappa_\parallel$ is the component of the difference vector $\vec{\kappa}$ along the magnetic field, and $\Omega = \omega - \omega'$.

## 3 Scattering of ECM radiation into a "window" of transparency

As we noted in the Introduction, as the radiation propagates through regions with weaker magnetic fields where $\omega = s\omega_{\rm Be}$ ($s = 2, 3, 4...$), cyclotron absorption leads to strong attenuation of the radio emission, with the dominant contribution being given by absorption at the second harmonic of the gyrofrequency, $s = 2$.

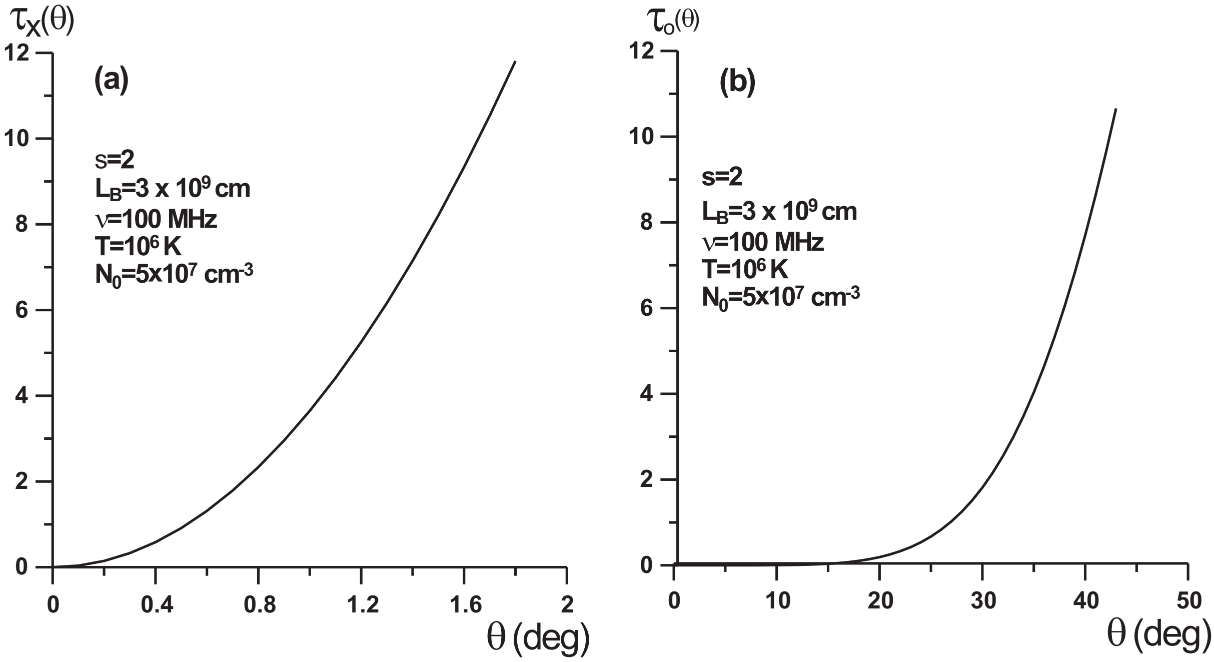


*Figure 1: Dependence of the optical depth to cyclotron absorption in a layer with $s = 2$ on the angle between the magnetic field and the wave vector for the extraordinary (a) and ordinary (b) waves.*

Figure 1 shows the optical depth to gyroresonance absorption of extraordinary (a) and ordinary (b) waves at the second harmonic of the gyrofrequency, $s = 2$, as a function of the angle $\theta$ between the wave vector and the magnetic field. The plasma is assumed to be Maxwellian, with the temperature $T = 10^6$ K and the density $N_0 = 5 \times 10^7$ cm$^{-3}$ in the solar corona. The characteristic scale for variations in the magnetic field in the source of radio emission (a coronal magnetic arch) was taken to be $L_{\rm B} = 3 \times 10^9$ cm. It is seen in Fig.1 that there is only one narrow "window" along the magnetic field with the width $\Delta\theta_{\rm W} < 0.5^\circ$ for the extraordinary wave and with the width $\Delta\theta_{\rm W} < 25^\circ$ for the ordinary wave. In addition, there is another "window of transparency" for the ordinary wave with a width of a fraction of a degree near the orthogonal direction of propagation. However, we will see below that this window does not play a significant role in the escape of radiation from the source. The ECM radiation is generated at an angle $\theta \simeq 70^\circ$ to the magnetic field in a narrow cone with the width $\Delta\theta \simeq 3^\circ$ [Aschwanden, 1990], so that propagation of the radiation without appreciable attenuation is possible only if the scattering concentrates a substantial fraction of the radiation in the windows of transparency.

If the plasma in the radio source is sufficiently rarified ($\omega_{\rm Pe}/\omega_{\rm Be} < 0.2{-}0.4$), then the ECM mechanism generates primarily extraordinary waves [Aschwanden, 1990]. The frequency spectrum of the radiation is fairly narrow. When $\omega_{\rm Pe}/\omega_{\rm Be} \simeq 0.1$, the relative width of the spectrum is $\Delta\omega/\omega \simeq 3\times10^{-2}$, with its maximum at $\omega_{\rm m} \simeq 1.03\omega_{\rm Be}$ [Aschwanden, 1990], which corresponds to the wave vector $k_{\rm m} \simeq 0.5\omega_{\rm Be}/c$. Scattering by magnetized ions dominates in the temperature interval $T \simeq 10^6 - 10^7$ K. This scattering is differential in frequency, since the width of the core of the integral equation (1) is smaller than the width of the frequency spectrum of the excited electromagnetic waves; i.e., $\kappa_{\parallel} v_{\rm Ti} \ll \Delta\omega$. The scattering is integral in angle, i.e., the direction of the wave vector k can be appreciably changed in a single scattering act. Taking into account the differential character of the scattering in frequency and the small angular width of the excited spectrum, Eq. (1) can be written in the form

$$\frac{\partial W_{\vec{k}}}{\partial t} = \frac{\sqrt{8\pi a}\,\omega_{\rm Pe}^4 v_{\rm Ti}}{\omega_{\rm Be}^3 N_0 \kappa_{\rm B} T_{\rm i}} \left(1+\frac{T_{\rm e}}{T_{\rm i}}\right)^{-2} \Psi_{\sigma\sigma'}(\theta,\theta')(k')^2 \left(\frac{k}{k'}\cos\theta - \cos\theta'\right)^2 W_{\vec{k}} \frac{\partial W_{k'}}{\partial\omega}, \qquad (5)$$

where $\kappa_{\rm B}$ is Boltzmann's constant, $W_{k'} = \int W_{\vec{k}'} d\Omega'$ is related to the energy density of the excited waves by the expression $W' = \displaystyle\int (k')^2 W_{k'} dk'$, $\Omega'$ is the solid angle in the space of $\vec{k}'$, $W_{\vec{k}}$ is the abbreviated form of $W_\sigma(\vec{k})$, and by $\theta$ and $\theta'$, which are the angles between the magnetic field and the wave vectors after and before the scattering, $N_0$ is the plasma density, and $a \simeq 2.7$. The dependence of the function

$$\Phi_{\sigma\sigma'}(\theta,\theta') = \Psi_{\sigma\sigma'}(\theta,\theta')(\frac{k}{k'}\cos\theta - \cos\theta')^2 \qquad (6)$$

on $\theta$ with $k = k'$ is presented in Fig. 2. Figure 2a corresponds to the scattering of an extraordinary wave into an extraordinary wave $\Phi_{\rm xx'}(\theta,\theta')$ for the case $\omega_{\rm Pe}/\omega_{\rm Be} = 0.3$, $\theta' = 70^\circ$ for various values of $\omega/\omega_{\rm Be}$. Figure 2b corresponds to the scattering of an extraordinary wave into an ordinary wave $\Phi_{\rm ox'}(\theta,\theta')$ for the same parameters. A comparison of these two figures shows that the increment for scattering an extraordinary wave into an extraordinary wave is approximately two orders of magnitude greater than that for scattering into an ordinary wave. Therefore, extraordinary waves will dominate in the spectrum of the scattered waves. In addition, it follows from the form of Eq.(5) and Fig. 2a that the scattering probability grows as the angle $\theta$ between the wave vector of the scattered wave and the magnetic field decreases. This means that, if the optical depth of the source to the process $x' \rightarrow x$ is sufficiently high, a narrow condensate of scattered extraordinary waves will arise along the magnetic field, which will propagate through the window of transparency along the magnetic field.

The appearance of this condensate is associated with the angular dependence in the argument of the exponential in the case of an exponential growth in the energy density of the scattered waves, described by Eq.(5). We obtain from Eq.(5) an estimate of the increment of the scattered radiation:

$$\gamma_{\rm xx'} = \sqrt{8\pi a}\,\omega_{\rm Pe}\frac{\omega_{\rm Pe}^3}{\omega_{\rm Be}^3}\left(1+\frac{T_{\rm e}}{T_{\rm i}}\right)^{-2} \frac{W'}{N_0\kappa_{\rm B}T_{\rm i}}\frac{k'_*}{\Delta k'}\frac{k'_* v_{\rm Ti}}{\Delta\omega'}\Phi_{\rm xx'}(\theta,\theta'). \qquad (7)$$

Here, $k'_*$, $\Delta k'$, and $\Delta\omega'$ are the characteristic values of the wave number and the widths of the spectrum generated in the source of ECM radiation.

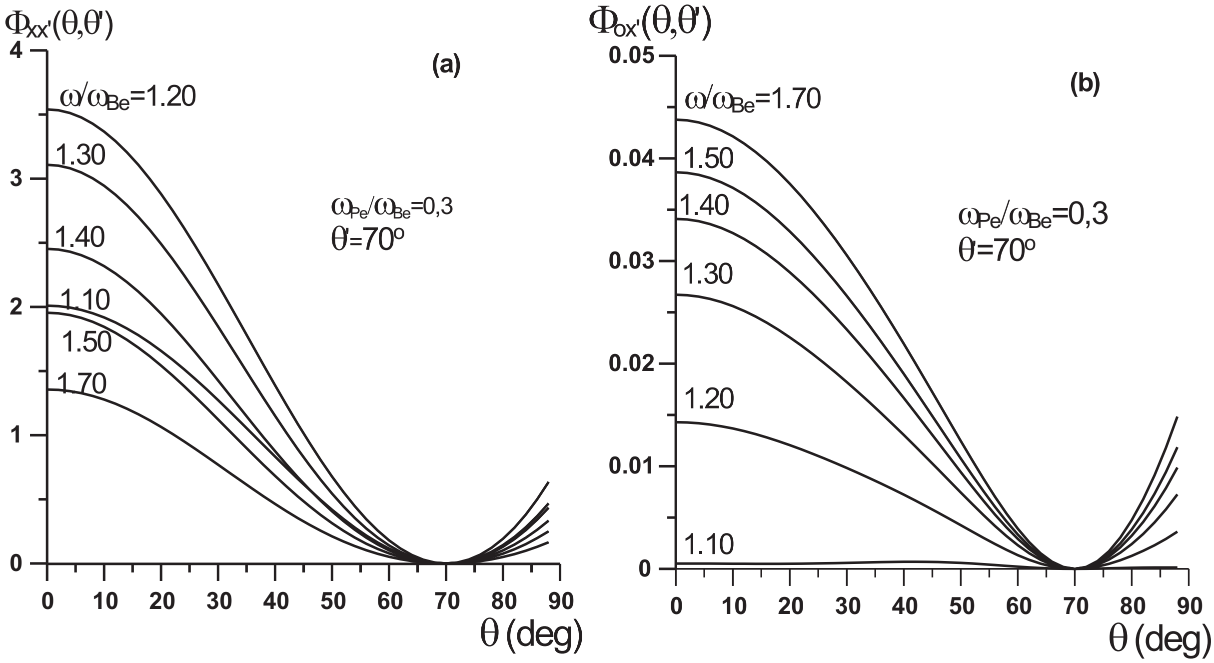


*Figure 2: Dependence of the probability of induced scattering of an extraordinary wave into extraordinary (a) and ordinary (b) waves on the angle $\theta$ between the wave vector of the scattered wave and the magnetic field for $\theta' = 70°$ and various frequencies.*

Since the magnetic field in the source is inhomogeneous with a scale $L_{\rm B}$ and the frequency of the radiation is close to $\omega_{\rm Be}$, a wave of a specified frequency $\omega'$ will interact with the excited waves until $\omega_{\rm Be}$ has changed along the ray path by an amount of the order of the width $\Delta\omega'$ of the spectrum of the excited waves. Therefore, we can adopt $\Delta x = \dfrac{\Delta\omega'}{\omega'} L_{\rm B}$ as the effective length of the region in which waves of a specified frequency $\omega'$ are scattered. The optical depth of the region with length $\Delta x$ to induced scattering will be

$$\tau_{\rm xx'} = \frac{\gamma_{\rm ee'}\Delta x}{v_{\rm gr}(\omega,\theta)} \simeq \frac{\gamma_{\rm ee'}\Delta\omega' L_{\rm B}}{\omega' v_{\rm gr}(\omega,\theta)}. \quad (8)$$

We can see from Eq.(8) that the optical depth to induced scattering depends on the energy density of the electromagnetic waves excited by the ECM mechanism. This energy density is determined both by the efficiency of the induced scattering causing the generated waves to go out of resonance with the fast particles responsible for the ECM instability, and by quasilinear effects that lead to deformations of the fast-particle distribution function and tend to suppress the instability. Our analysis shows that these quasilinear effects are more important in our case. In the case of ECM radiation, such quasilinear effects lead to an energy density for the electromagnetic waves in the source $W' \simeq 5 \times 10^{-3} N_{\rm h} \kappa_{\rm B} T_{\rm h}$, which is virtually independent of the magnitude of $\omega_{\rm Pe}/\omega_{\rm Be}$, the "temperature" of the radiating particles $T_{\rm h}$, and the degree of anisotropy of the fast-particle distribution function in terms of the particle velocities perpendicular to the magnetic field [Aschwanden, 1990].

One of the types of sporadic radio emission of the Sun that could be produced by the ECM mechanism are so-called type I noise storms. The radio emission of noise storms displays a high degree of circular polarization, long durations (up to several hours), a high brightness temperature, and a burstlike character. As a rule, the sources of type I noise storms are located near sunspots [Zheleznyakov, 1964]. If we suppose that the emission associated with these noise storms arises at $\omega \simeq \omega_{\rm Be}$, then a characteristic frequency of $\nu = 100$ MHz corresponds to the source magnetic field $B \simeq 36$ G. If $\omega_{\rm Pe}/\omega_{\rm Be} \leq 0.3$, then we obtain the plasma density $N_0 \leq 1.2 \times 10^7$ cm$^{-3}$ in the radio source. Assuming that the temperature of the plasma in the solar corona is $T \simeq 10^6$ K, the temperature of the hot particles is $T_{\rm h} \simeq 3 \times 10^8$ K, and $L_{\rm B} \simeq 3 \times 10^9$ cm (of the order of a sunspot diameter), we obtain for the optical depth in the solar corona

$$\tau_{\rm xx'} \simeq 10^5 \frac{N_{\rm h}}{N_0} (\cos\theta - \cos\theta')^2 \tag{9}$$

and for the width of the angular spectrum of the extraordinary waves in the condensate that arises along the magnetic field as a result of the induced scattering

$$\Delta\theta \simeq 1.5 \times 10^{-1} \left(\frac{N_0}{N_{\rm h}}\right)^{1/2} \text{ deg}, \tag{10}$$

which, for $N_{\rm h}/N_0 = 10^4$, gives the angular width $\Delta\theta \simeq 5°$. As is shown in Fig. 1a, which presents the angular dependence of the optical depth to gyroresonance absorption for $s = 2$ (gyroresonance absorption is appreciably lower for $s = 3$), the width of the window of transparency (in which $\tau < 1$) is $\Delta\theta_{\rm W} \simeq 0.5°$. In this case, the transmission coefficient of the window for extraordinary radiation is $(\Delta\theta_{\rm W})^2 \simeq 2.5 \times 10^{-3}$ ; i.e., only a very small fraction of the scattered radiation can escape from the source in the form of an extraordinary wave.

The induced scattering of an ordinary wave into an ordinary ($o' \to o$) or extraordinary ($o' \to x$) wave is also described by Eq.(5) if $\Psi_{\sigma\sigma'}(\theta, \theta')$ is replaced by $\Psi_{oo'}(\theta, \theta')$ or $\Psi_{xo'}(\theta, \theta')$, respectively, and we take the spectrum of the excited ordinary waves for $W_{\vec{k}'}$. The angular spectrum of the scattered radiation will be

$$W_{\vec{k}}(\theta) \simeq W^0_{\vec{k}}\, e^{\tau_{\sigma o'}(\theta)}, \qquad \tau_{\sigma o'} \simeq 2 \times 10^{-2} \frac{N_{\rm h} T_{\rm h}}{N_0 T} \frac{\omega^4_{\rm Pe}}{\omega^4_{\rm Be}} \frac{v_{\rm Ti}}{c} \frac{\omega_{\rm Be} L_{\rm B}}{v_{\rm gr}(\omega, \theta)} \Phi_{\sigma o'}(\theta) \tag{11}$$

where

$$\Phi_{\sigma o'}(\theta) = (\cos\theta - \cos\theta')^2\, \Psi_{\sigma o'}(\theta, \theta')|_{\theta' = 70°}\,. \tag{12}$$

We can see from Eqs.(11) and (12) that the optical depth $\tau_{\sigma o}$ grows with the ratio $\omega_{\rm Pe}/\omega_{\rm Be}$, reaching its maximum value at the outer boundary of the region in which predominantly ordinary waves are generated, i.e., where $\omega_{\rm Pe}/\omega_{\rm Be} \simeq 1$. Figure 3 shows the dependence of the function $\Phi_{\rm oo'}(\theta, \theta' = 70ø)$ on the scattering angle for $\omega_{\rm Pe}/\omega_{\rm Be} = 1$ and various values $\omega/\omega_{\rm Be}$. The dashed curve shows the dependence $\Phi_{\rm xo'}(\theta, \theta' = 70ø)$ for $\omega/\omega_{\rm Be} = 1.7$, i.e., for a frequency exceeding the cutoff frequency for the extraordinary waves, at which these waves can escape from the source. We can see that scattering into an ordinary wave is appreciably more efficient than scattering into an extraordinary wave, and this latter process can be neglected. The function $\Phi_{\rm oo'}(\theta, \theta' = 70ø)$ has a relatively sharp maximum, which falls into the window of transparency for ordinary waves when $\omega/\omega_{\rm Be} = 1.02 - 1.2$. This can easily be verified by using Fig. 1b.

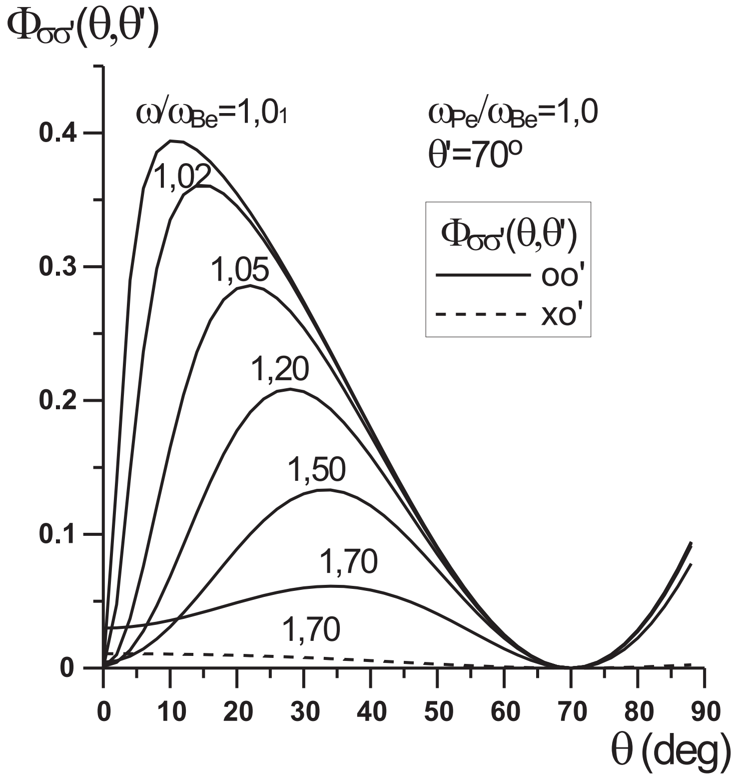


*Figure 3: Dependence of the probability of induced scattering of an ordinary wave into ordinary and extraordinary waves on the angle $\theta$ between the wave vector of the scattered wave and the magnetic field for $\theta' = 70°$ and various frequencies.*

Let us estimate the optical depth to induced scattering for the parameters characteristic of type I noise storms, assuming that ordinary waves are excited in the source by the ECM mechanism. We assume that $\omega_{\rm Be} \simeq 6 \times 10^8$ rad s$^{-1}$ (the radiation frequency is about 100 MHz), $\omega_{\rm Pe}/\omega_{\rm Be} = 1$, $T = 10^6$ K, $T_{\rm h} = 3 \times 10^8$ K, $L_{\rm B} = 3 \times 10^9$ cm. The optical depth

$$\tau_{\rm oo'}(\theta) \simeq 7 \times 10^{11} \cos^n(\theta - \theta_{\rm m}) \frac{N_{\rm h}}{N_0}, \tag{13}$$

where $n \simeq 10$ has a sharp maximum near $\theta_{\rm m} \simeq 15°$, with angular width of

$$\Delta\theta \simeq \frac{3,7 \times 10^{-3}}{n} \left(\frac{N_0}{N_{\rm h}}\right)^{1/2} \text{ rad.} \tag{14}$$

The scattering is efficient if the density of fast particles in the source is sufficiently high, $N_{\rm h}/N_0 \gg 1.4 \times 10^5$. The maximum width of the angular spectrum of the scattered waves is $\Delta\theta_{\rm max} \simeq 5.6°$. Since the condensate of scattered waves falls into the "window" of transparency the radiation can freely leave the source.

## 4 Conclusions

Let us formulate the main conclusions of our analysis concerning the escape of electron-cyclotron maser radiation from the solar corona. If the magnetic field in the source is sufficiently strong ($\omega_{\rm Pe}/\omega_{\rm Be} < 0.25 - 0.4$), the ECM generates extraordinary waves near the electron gyrofrequency $\omega \simeq \omega_{\rm Be}$ at an angle $\theta' \simeq 70°$ to the magnetic field. In this case, the excited radiation is scattered predominantly into extraordinary waves at a smaller angle $\theta$. If the growth in the intensity of the scattered wave is exponential and the optical depth to induced scattering is fairly high (this will be the case if $N_{\rm h}/N_0 > 10^5$), this leads to the formation of a condensate near $\theta \simeq 0°$ with the angular width $\Delta\theta \simeq 15°$. The width of the window of transparency near $\theta \simeq 0°$ is appreciably smaller, $\Delta\theta \simeq 0.5°$. This means that only a small fraction of the radiation can escape from the source, $\sim 10^{-3}$ for the solar corona. The remaining radiation is absorbed as it propagates through the gyroresonance level s = 2. When $0.25 - 0.4 \leq \omega_{\rm Pe}/\omega_{\rm Be} \leq 1$ the ECM mechanism excites ordinary waves at an angle $\theta' \simeq 70°$ to the magnetic field. These waves are scattered predominantly into ordinary waves, with the probability of scattering growing as the angle between the magnetic field and the direction of propagation decreases, reaching its maximum at $\theta_{\rm m} \simeq 15°$, which is within the window of transparency for ordinary waves (Fig. 1b). The optical depth to scattering is high for $N_{\rm h}/N_0 \gg 1.4 \times 10^{-5}$. The angular width of the condensate of ordinary waves is $\Delta\theta \simeq 6°$, i.e., smaller than the window of transparency. This means if $\tau_{\rm oo} \gg 1$, then the bulk of the generated ECM radiation can leave the source as a result of induced scattering from the region of instability into a window of transparency for cyclotron absorption. Our analysis and comparisons indicate that if sources of powerful ECM radiation are realized in the corona of the Sun, the escaping radiation will be polarized primarily in the ordinary mode.

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