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ALTITUDE-DEPENDENT EMISSION OF TYPE III SOLAR RADIO BURSTS

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ABSTRACT

The present discussion complements a preceding article in which a cyclotron-maser theory of type III solar radio bursts is proposed. One important issue, which has not been addressed in any of the existing theories, is that in the event of a F-H pair emission dynamic spectra usually show an initial time delay of the fundamental (F) component after the harmonic (H) component has commenced. Moreover, the ratio of the starting frequencies of the H waves to those of the F waves is generally higher than 2. A plausible interpretation is that the emission of H waves starts at an altitude lower than that for F waves. This notion leads to the present study. Although it is formulated within the context of the cyclotron-maser scenario, the model of the source electrons is different from that discussed previously.

Subject headings: Sun: particle emission — Sun: radio radiation

1. INTRODUCTION

Early observations suggest that type III solar radio bursts are generated by a beam of fast electrons at times of flares, as extensively discussed in the literature (e.g., early publications are cited in Kundu [1965], and the latest review is presented in Dulk [2000]). Dynamic spectra show that the radiation seems to have typical frequencies close to the local plasma frequency and/or its second harmonic. This finding leads to the hypothesis of plasma emission, a term that was introduced in the classic papers by Wild & McCready (1950) and Wild (1950a, 1950b). As a result, scientists search for processes that can lead to plasma emission. A commonly adopted notion is that streaming electrons first excite Langmuir waves and then part of the energy of the enhanced Langmuir waves is converted into electromagnetic waves with frequencies close to the plasma frequency and its harmonic. It is on the basis of this notion that Ginzburg & Zheleznyakov (1958) proposed the first formal theory. This pioneering work has stimulated numerous subsequent works and has also profoundly influenced later theoretical efforts. Reviews of the early theories are given in Goldman (1983), Melrose (1985), and Goldman & Smith (1986). Improved plasma emission models are discussed and summarized by Robinson & Cairns (1998a, 1998b, 1998c). All proposed theories based on plasma emission rely on nonlinear conversion processes of enhanced Langmuir waves.

New theories of type III emission are needed for several reasons. First of all, almost all existing theories neglect the effect of the ambient magnetic field on the emission process, whereas observations find that metric and decametric type III bursts are produced above active regions where the magnetic field is stronger than that elsewhere at the same altitude. Furthermore, the observed radiation is intense, but most of the proposed theories rely on sophisticated, inefficient, multistep nonlinear processes. More importantly, there are outstanding issues that cannot be resolved in the context of the plasma emission hypothesis. Given these considerations, we feel strongly that it is desirable to go beyond the notion of nonlinear conversion of Langmuir waves and look for a new emission mechanism for type III bursts.

Several points deserve general attention. Not only do they have far-reaching implications, but they also provide us very important clues. They are outlined in the following:

1. In view of the situation that the emission generally occurs near active regions (Suzuki & Dulk 1985), we believe that the effect of magnetic fields on the emission process is more important than what previous authors had in mind.
2. Observations find that waves of the fundamental (F) component and the second harmonic (H) component of type III bursts with same frequency have coincidental source regions. This finding is reported and discussed in a number of publications (Smerd et al. 1962; Bougeret et al. 1970; McLean 1971; Stewart 1972, 1974a, 1974b; Dulk & Suzuki 1980). It implies that the nature of the F waves and H waves, as well as the observed source regions, deserves more study.
3. Another point seems to be very important. That is, early observations find statistically that F components with starting frequencies around 60 MHz occur most frequently, while H components with starting frequencies around 200 MHz are observed most often (e.g., Dulk & Suzuki 1980; Suzuki & Dulk 1985). Among the cases studied, H waves with starting frequencies above 160 MHz represent 59% of the total, whereas F waves with starting frequencies above 80 MHz represent only 24%. Moreover, F waves with starting frequencies above 160 MHz in the examples represent only less than 1%. From these results it seems that in general the emission of the H waves starts earlier than the F waves. It implies that the emission process may be altitude-dependent, a point that all previous theories have overlooked.

Points 1 and 2 lead us to propose a new theory, which is described in two recent articles (Wu et al. 2002; Yoon et al. 2002) in which we introduce (*a*) the notion of cyclotron-maser theory and (*b*) the concept of a true source region and an apparent source region. Although these discussions show that the new emission mechanism is promising, the scenario is unable to resolve the issue described in point 3, which has motivated us to continue the study.

The purpose of this paper is to complement the cyclotron-maser theory discussed in Wu et al. (2002) and to resolve the

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issue concerning starting frequencies of F-H pair emission that occurs in the low corona. We now consider a more realistic model of the source electrons that is altitude-dependent. In order to make the presentation self-contained, the principal elements are reiterated. The structure of the paper is as follows. In §§ 2–5 we describe the basic parts of the proposed scenario. Then in § 6 we present some numerical results for illustration purposes. Finally, we present discussion and conclusions in § 7.

2. BASIC CONSIDERATIONS

In the present theory we make two postulates at the outset. First, we postulate that density-depleted flux tubes exist in the low corona, as discussed in the preceding article by Wu et al. (2002). Since in general the coronal magnetic field originates below the photosphere, where the magnetic field is structured and nonuniform, we anticipate that the magnetic field in the corona is corrugated and not uniform. On the other hand, it is also well known that in a low-beta plasma a weak magnetic field nonuniformity can lead to a substantial density inhomogeneity. For example, let us consider a region where the plasma beta is low, say 10^{-2} or lower, and let us assume that the total pressure in a flux tube is in equilibrium with that outside the tube. Then a 1% increase of the magnetic field inside the tube is sufficient to deplete the interior density to a very low level. On the basis of this consideration, we expect that in the low corona, particularly near active regions, density-depleted flux tubes may exist pervasively. This assumption is supported by observations that show fibrous density structures in the corona (e.g., Koutchmy 1977). Apparently these structures consist of highly overdense and underdense filaments, which usually have very long lengths that extend into interplanetary space.

Second, we assume that energetic particles are generated somewhere above an active region. One of the plausible causes is magnetic reconnection that is discussed in various solar flare models (e.g., Sturrock 1980; Masuda et al. 1994; Innes et al. 1997; Priest & Forbes 2002). In general, these energetic particles may occur either inside or outside the density-depleted flux tubes. In the present discussion we are only interested in those occur inside those flux tubes with low density.

3. MIRROR REFLECTION OF PRECIPITATING ELECTRONS

In general, the energetic particles created above an active region may move away from the site of generation along open field lines in both upward and downward directions. Conventionally, it is assumed that the downward electrons result in the emission of hard X-rays, while the upward electrons generate type III radio bursts. However, in this paper we present a different view.

It is conceivable that under certain conditions a fraction of the downward electrons may be reflected owing to conservation of magnetic moment. If the local magnetic field at the generation site is B_s and the magnetic field in the chromosphere is B_0, the loss-cone angle ϑ_c at the generation site is then

$$\vartheta_c = \sin^{-1}\sqrt{B_s/B_0}.$$

This means that those downward electrons with pitch angles greater than ϑ_c are reflected. Figure 1a schematically depicts the momentum distribution of a downward beam at the generation site, while Figure 1b describes that of the reflected electrons. The actual situation is slightly more complicated than what we have said. Since in general protons are not reflected because of their small pitch angles, we expect that an electric field parallel to the ambient magnetic field would take place near and above the chromosphere. If we denote the associated electrostatic potential difference between altitude h and the reflection point by $\triangle\phi$, then the loss-cone angle is modified so that

$$\vartheta_c = \sin^{-1}\sqrt{\frac{B_s}{B_0}\left(1+\frac{2e\triangle\phi}{mv^2}\right)} \tag{1}$$

(hereafter we postulate that the potential $\triangle\phi$ reaches its asymptotic value far below the generation site). We point out that this postulate should be studied further. Hence the electric field tends to widen the loss-cone angle. In the following we consider that $2e\triangle\phi/mv^2 \sim O(1)$.

To facilitate the following discussion we adopt a certain magnetic field model and density model, which are displayed in Figures 2 and 3. Several remarks on this magnetic field model may be necessary. First of all, we point out that the magnetic field used in Wu et al. (2002) may be too strong for a general discussion. Therefore, we consider a new model, which is displayed in Figure 2. Here the magnetic field shown is the strength along an open flux tube of interest. It is expressed as a function of altitude R measured from the surfaces of the Sun. It consists of two parts: one is an ambient field that is inversely proportional to the square of altitude, and the other is attributed to an active region. The total magnetic model field is expressed as

$$B = \frac{B_1}{(R+1)^2} + B_2\left(1-\frac{R}{\sqrt{R^2+b^2}}\right). \tag{2}$$

Hereafter let us consider $B_1 = 1$ G and $B_2 = 100$ G at the chromosphere. The sunspot field is modeled as a unipolar field. In equation (2) R denotes altitude, and b approximately describes the dimension of a sunspot. Both R and b are in units of solar radius. We reiterate that this model is used for the purpose of illustration. It is understood that in general B_2 can vary from case to case. However, $B_2 = 100$ G is chosen following Dulk & McLean (1978). Another point that needs emphasis is that in general this flux tube is curved, and not necessarily in the radial direction. Evidently this model is very different from that used in Wu et al. (2002), which has an intensity of 1000 G at the surface of the Sun. That magnetic field model leads to an impression that the cyclotron-maser theory is operative only under such an extreme condition.

Making use of the new magnetic field model, we can readily calculate the loss-cone angle based on equation (1). The result is displayed in Figure 4. If we consider that the bulk momentum u_0 is $0.2c$, or 6×10^4 km s^{-1}; the beam electron distribution has a dispersion 10^4 km s^{-1}, and the average pitch angle is about 10°. This means that if the generation site is situated around 2×10^4 km above the chromosphere, a fraction of downward beam electrons may be reflected. We propose that those reflected electrons are responsible for the type III bursts because they can lead to a cyclotron-maser instability as they ascend along open field lines.

4. CYCLOTRON-MASER INSTABILITY

An approximate theory of cyclotron-maser instability associated with a population of energetic electrons with a loss-cone distribution was first derived and discussed in Wu & Lee (1979). A more general expression for the growth rate or absorption coefficient is later discussed in the literature (Melrose 1986; Benz 1993). If ω_{qi} denotes the absorption coefficient of a

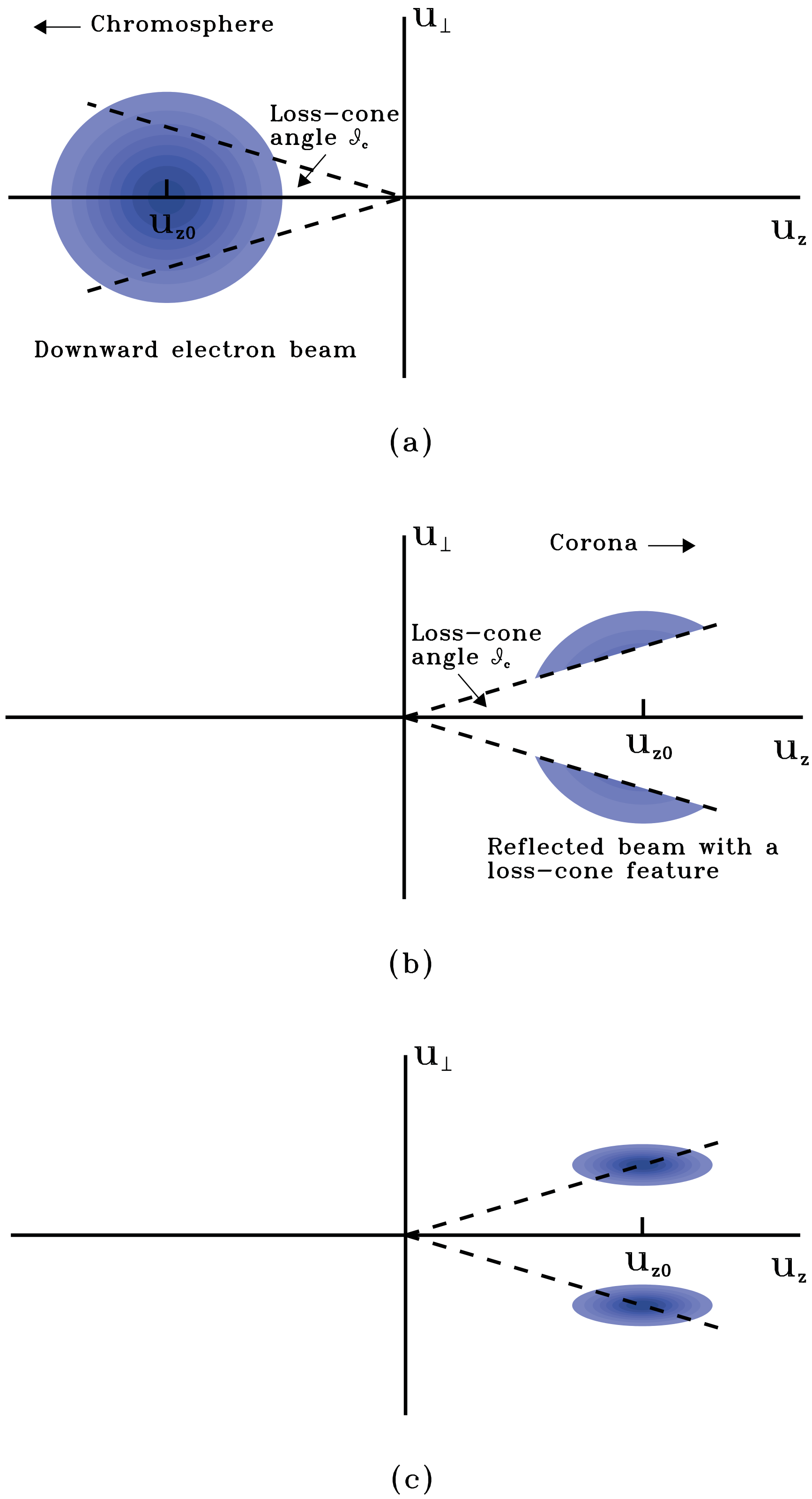

FIG. 1.—Momentum distribution function of a beam of electrons viewed from a generation site above an active region; $u_\perp$ and u_z denote the components of momentum per unit mass perpendicular and parallel to the ambient magnetic field, respectively. Displayed are (*a*) the downward beam electrons, (*b*) the reflected electrons with a loss-cone feature, and (*c*) the electrons modeled by eq. (7). Darker color marks higher population of electrons.

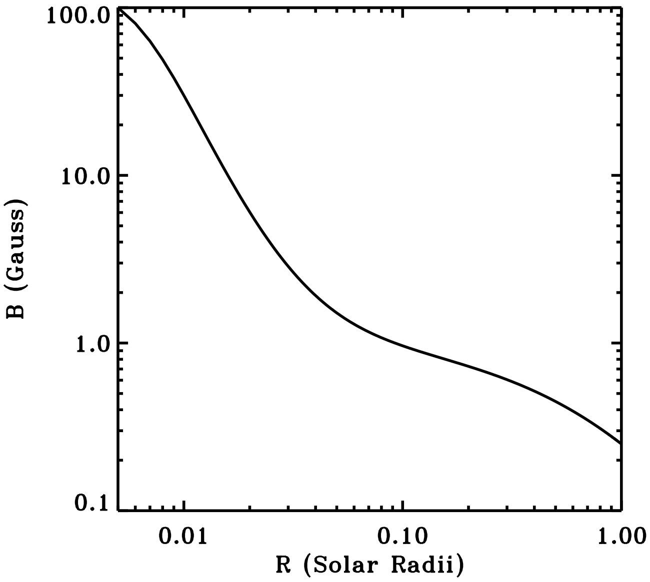

FIG. 2.—Magnetic field strength as a function of altitude is displayed. This model has a magnetic field of about 100 G at the bottom of the corona. The altitude, R, is expressed in units of solar radius.

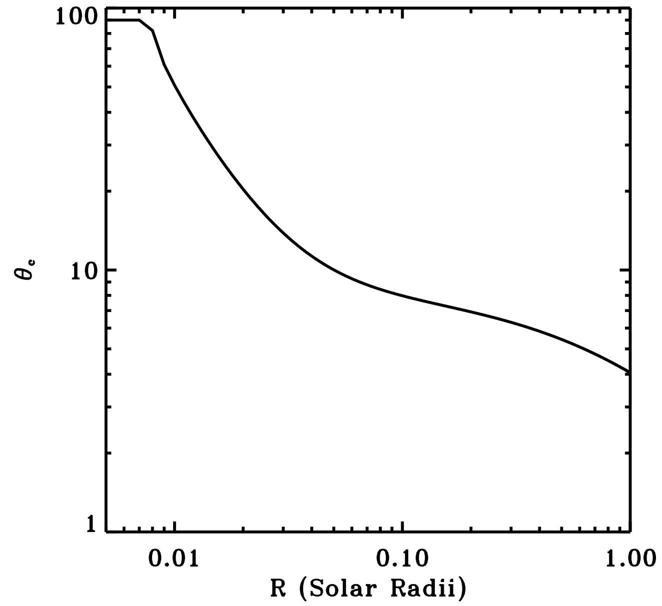

FIG. 4.—Calculated loss-cone angle as a function of altitude is displayed. In the calculation we consider $2e\triangle\phi/mv^2 \approx 1$.

wave of mode q with frequencies close to the nth harmonic, a simplified expression may be written as

$$\omega_{qi} = G_q \int d^3\boldsymbol{u} u_\perp \left(\frac{k_\perp u_\perp}{2\Omega}\right)^{2(n-1)} \frac{\partial F_b}{\partial u_\perp} \delta(\gamma\omega_q - n\Omega - k_z u_z), \tag{3}$$

where $F_b(\boldsymbol{u})$ is the distribution function of the beam electrons, Ω is the electron gyrofrequency, and

$$G_q = G_q(\omega_q, \theta) \tag{4}$$

is, as defined in the Appendix, in general a positive function of frequency ω_q and wave normal angle θ. In equations (3) and (4), N_q is the refractive index of a wave of mode q, u is the momentum per unit mass, and ω_p is the plasma frequency. So far we have specified that if $\omega_{qi} < 0$, we have absorption, and if $\omega_{qi} > 0$, we have emission. In obtaining equations (3) and (4) we have considered

$$\frac{N_q u_z}{c} \ll 1,$$

$$b_q = N_q \frac{\omega_q}{\Omega} \frac{u_\perp}{c} \sin\theta \ll 1,$$

where the subscript $\perp$ denotes component perpendicular to the ambient magnetic field. Only in the delta function that appears in equation (3) do we consider relativistic effect. From equation (3) we see that a positive ω_{qi} (emission) can occur if

$$\left.\frac{\partial F_b(\boldsymbol{u})}{\partial u_\perp}\right|_{u=u_R} > 0, \tag{5}$$

where u_R is the resonant momentum that satisfies the resonance condition, which is the argument of the delta function in equation (3),

$$\gamma\omega_q - n\Omega - k_z u_z = \gamma\omega_q - n\Omega - \omega_q N_q \cos\theta u_z/c = 0, \tag{6}$$

where $\gamma = (1 + u^2/c^2)^{1/2}$ is the relativistic factor, ω_q is the real part of the wave frequency, $\Omega = |eB/mc|$ is the electron gyrofrequency, n is a harmonic number, and u_z and k_z are components of the momentum $\boldsymbol{u}$ and wave vector $\boldsymbol{k}$ parallel to the ambient magnetic field $\boldsymbol{B}$, respectively. Obviously the loss-cone–beam distribution illustrated in Figure 1b can easily satisfy the instability criterion (eq. [5]). However, it is not convenient to express it analytically for numerical calculation. For this reason, we model the reflected electrons at low altitudes by the following model:

$$F_b(u_z, u_\perp) = C \exp\left[-\frac{(u_\perp - u_{\perp 0})^2}{\alpha^2} - \frac{(u_z - u_{z0})^2}{\beta^2}\right], \tag{7}$$

where C is a normalization constant, $u_{\perp 0}$ is a ring momentum, u_{z0} is the beam momentum, and α and β are momentum

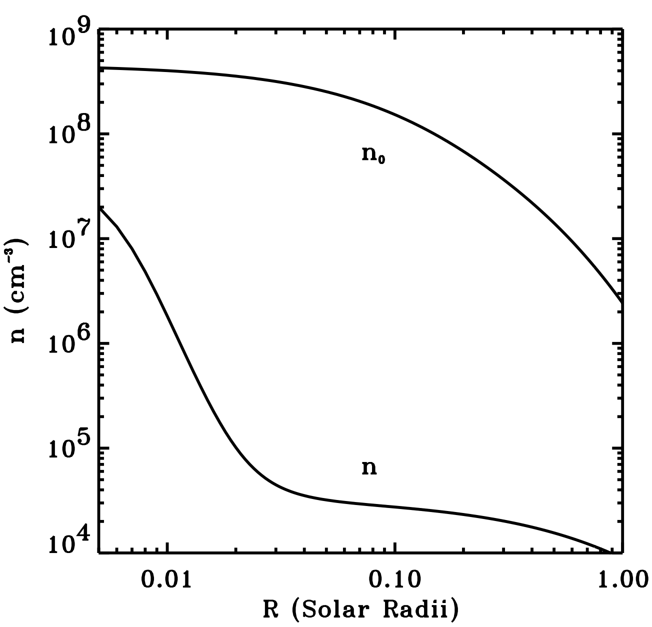

FIG. 3.—Density inside and outside a flux tube as a function of altitude.

dispersions that may vary with altitude. Function (7) retains the essential features of that depicted in Figure 1*b*. To illustrate this point we illustrate equation (7) schematically in Figure 1*c*. Qualitatively, the loss-cone feature may be described by the quantities $u_{\perp 0}$ and u_{z0}, which are in general altitude-dependent. Hereafter we consider that at altitude h

$$\frac{u_{\perp 0}(h)}{u_{z0}(h)} = \tan \vartheta_c(h), \tag{8}$$

where $\vartheta_c(h)$ is the local loss-cone angle, $B(h)$ is the local magnetic field, and B_0 denotes the magnetic field at the top of the chromosphere. We have implicitly assumed in equation (8) that magnetic moment is conserved. If there is no significant dissipation and heating in the region of interest, we may assume that

$$u_{\perp 0}^2 + u_{z0}^2 = \text{const.} \tag{9}$$

Making use of equations (3), (7), (8), and (9), we can discuss the emission coefficient at different altitudes. For the purpose of the numerical calculation we model the distribution function (eq. [6]) such that $\alpha^2/\beta^2 = u_{\perp 0}^2/u_{z0}^2$.

Numerical study of the instability finds that in general the frequency ratio $\omega_p/\Omega \equiv f_p/f_g$ is an important parameter. Generally, H waves are amplified in regions where the ratio is within the range $0 < f_p/f_g < 1.4$, but the F waves can be amplified only when the ratio is small, say $0 < f_p/f_g < 0.3$. These findings are in qualitatively good agreement with those obtained in Wu et al. (2002) and Chen et al. (2002), although in the present case the magnitude of the emission coefficient is generally much larger. In short, both the parameter f_p/f_g and the loss-cone angle play essential roles in the present theory. The numerical results of the emission coefficient as a function of altitude will be discussed later.

5. TRUE SOURCE REGIONS AND APPARENT SOURCE OF EMISSION

We believe that the observed source regions of F and H waves are actually apparent source regions rather than the true source regions, as discussed in Wu et al. (2002). We reiterate that inside a density-depleted flux tube the cutoff frequency of either the *X*-mode or the *O*-mode is significantly lower than that outside the tube. Thus, if the true source region, where a wave is generated, is situated inside the flux tube, and if the wave frequency is below the exterior cut-off frequency, the wave is confined in the tube during propagation (thus, the true source is not observable). This wave cannot leave the tube until it reaches an altitude where the local exterior cutoff frequency becomes lower than the wave frequency. Hence, waves, regardless the locations of their generation, with the same frequency would exit at the same altitude.

Indeed, the interior density distribution as a function of altitude can only be hypothesized. The model assumed in this discussion is based on three considerations: (1) immediately above the chromosphere newly ionized gas at the topside of the chromosphere may enter a density-depleted duct so that the level of depletion is reduced, (2) at the generation site where compression occurs, the depletion is maximum, and (3) intuitively we also believe that above the generation site the depletion decreases slowly with altitude. The model of interior density is described in Figure 3. The exterior and interior *X*-mode cutoff frequencies are plotted in Figure 5 in which the electron gyrofrequency and its second harmonic are also shown.

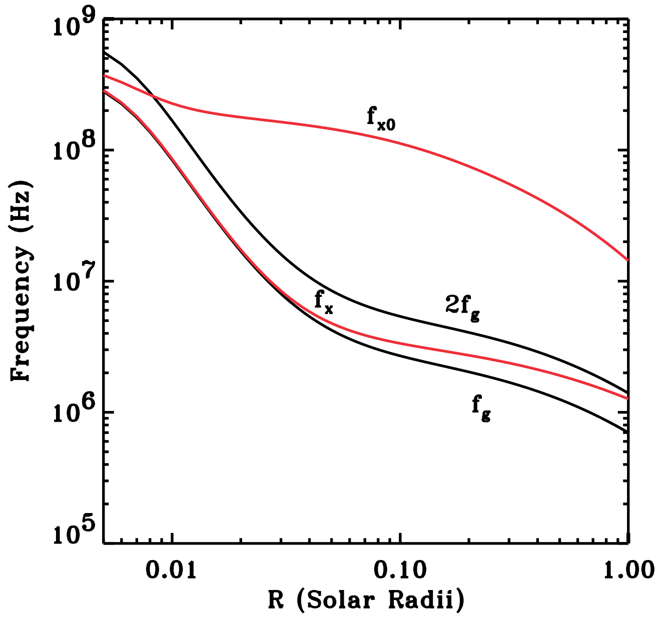

Fig. 5.—Electron gyrofrequency f_g and its second harmonic $2f_g$ vs. altitude are shown. The *X*-mode cutoff frequency of the plasma outside the duct, f_{X0}, and that of the plasma inside, f_X are also displayed. The interior cut-off frequency is calculated on the basis of the density model assumed for electrons inside the duct.

On the basis of the above considerations the present theory suggests that in the true source region the emitted waves have frequencies either close to the local gyrofrequency and/or its second harmonic. However, at the exit point, the apparent source, their frequencies are close to the local plasma frequency. (At high altitudes outside the tube the ratio $\omega_p/\Omega \gg 1$, so that the exterior cut-off frequency is approximately equal to the local plasma frequency.) Hence, two salient conclusions are evident: (1) the proposed scenario explains that an F wave and an H wave with same frequency have coincidental source regions because they exit at the same point, and (2) the observed radiation gives us an illusion that the emitted waves have frequencies close to the plasma frequency in the (apparent) source region.

6. EMISSION OF H AND F WAVES VERSUS ALTITUDE

For illustration purpose we now discuss the emission coefficient at low and high altitudes based on equations (3), (7), (8), and (9). Here we emphasize two points: (1) In the present model the distribution function of the reflected beam electrons varies with altitude while they ascend. At low altitudes, immediately after reflection the electron energy is mainly in the ring momentum, while at high altitudes the energy is in the beam momentum. (2) According to the present model, we expect that F waves cannot be emitted at low altitudes, because F waves require a sufficiently large beam momentum, while H waves can be amplified with a ring distribution. This expectation is verified by numerical computation.

To carry out the calculation we shall consider a situation discussed in the following. In the present discussion we consider $u_0 = 0.2c$. This is based on the discussion in Dulk et al. (1987) in which the authors argue that the electron beam velocity may be lower than that estimated in the earlier literature. We also assume a hypothetical interior density profile that leads to the ratio f_p/f_g in Figure 6. We suppose that the beam electrons are generated at 0.03 solar radii where the loss-cone angle is about 10° according to the magnetic field model used. The maximum emission coefficient as a function of altitude is computed.

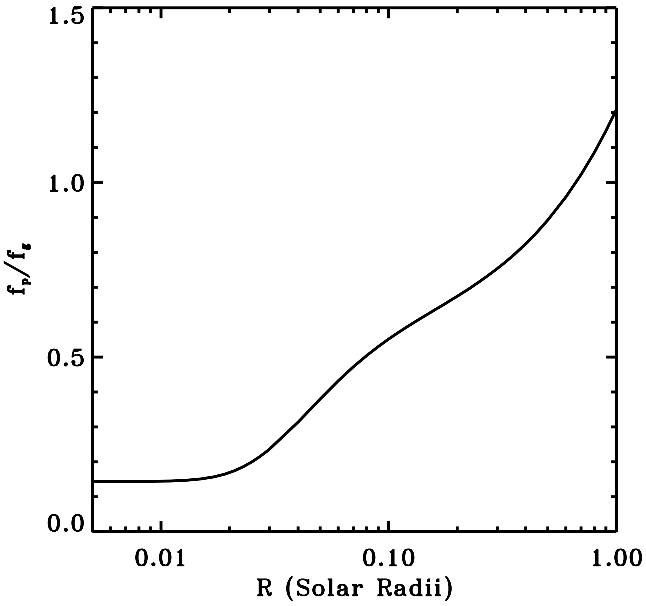

FIG. 6.—Ratio f_p/f_g inside a density-depleted duct is displayed. It is calculated on the basis of the models under consideration.

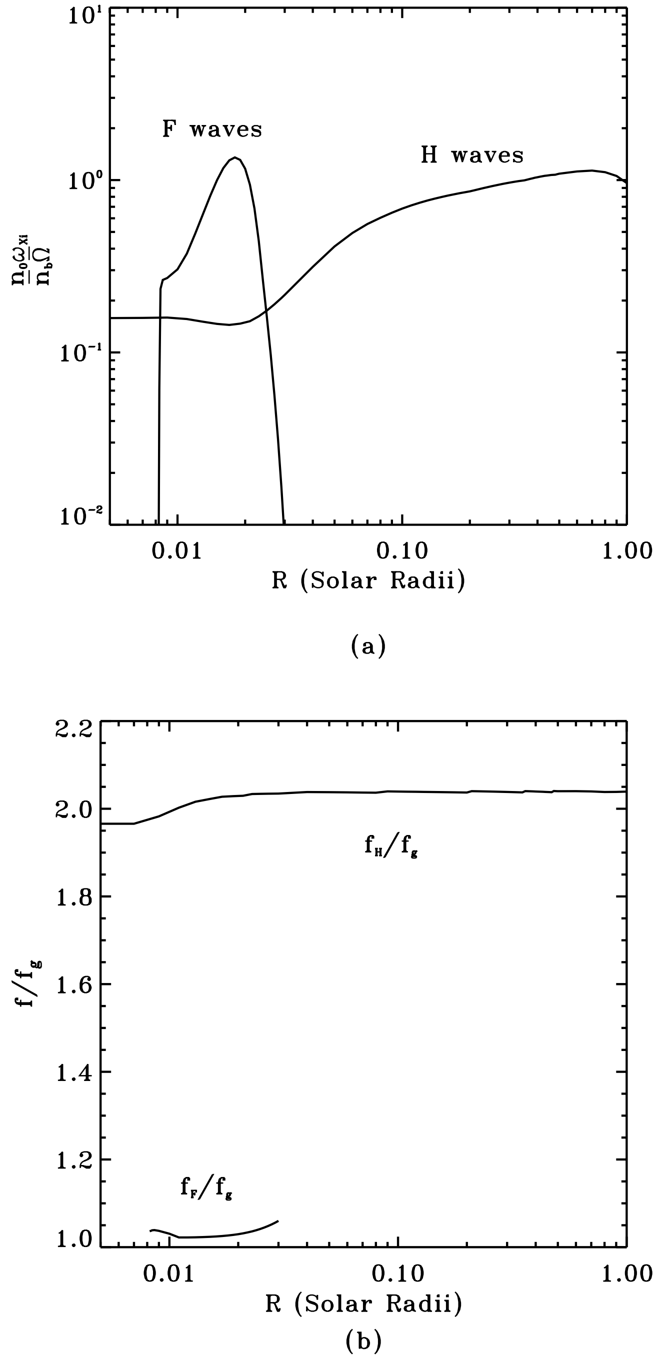

FIG. 7.—Results displayed are obtained by considering $u_0 = 0.2c$, $\alpha = 0.1u_{\perp 0}$ and $\beta = 0.1u_{z0}$. (*a*) The normalized maximum emission coefficient $(\omega_{Xi}/\Omega)(n_0/n_b)$ is calculated for the altitude range $0 < R \leqslant 1$, which corresponds to the range of electron gyrofrequencies 0.5 MHz $< f_g <$ 280 Mhz. (*b*) The normalized frequencies f_F/f_g and f_H/f_g of the emitted F waves and H waves at different altitudes are displayed. It is assumed that waves with $(\omega_{Xi}/\Omega)(n_0/n_b)$ less than 10^{-2} are insignificant and negligible.

The result is shown in Figure 7*a*. The corresponding wave frequencies normalized by the local gyrofrequency are plotted in Figure 7*b* from which we see that H waves are generated at altitudes lower than F waves, as expected. To summarize, Figure 8 displays the frequencies (corresponding to the maximum emission coefficients) of the two components versus altitude from which the threshold altitude of the F components is shown. In the above discussion we assume that waves with normalized emission coefficient less than 10^{-2} are unimportant and negligible. Before closing we remark that in the present discussion we only calculated the temporal growth rate, which is equivalent to the emission coefficient in the discussion of induced radiation. We did study the spatial amplification rate in Wu et al. (2002). The temporal growth rates in the present model are in general at least 1 order of magnitude higher. Thus, we expect that the spatial amplification rates are also much higher.

7. DISCUSSION AND CONCLUSIONS

From the preceding discussion we can now explain why H waves usually have starting frequencies higher than those of F waves. At low altitudes the reflected electrons, because of their large pitch angles, cannot amplify the F waves, but they have no difficulty amplifying the H waves. This point also explains the observed initial delay of the F component after the onset of the H component, an issue that has intrigued scientists for many years. In short, in general the emission of type III bursts is altitude-dependent. The effect of altitude on the emission process is more evident at low altitudes. As the altitude increases progressively, the loss-cone angle decreases gradually. Consequently, the emission coefficient also reduces accordingly. Eventually the cyclotron maser process diminishes at very high altitudes. Our preliminary conclusions are summarized as follows.

The emission of the H waves is much less restricted to the ratio f_p/f_g than the case of F waves, which require $f_p/f_g < 0.3$. Thus, we believe that in most cases in which only one component emerges the emission may be associated with H waves.

Theoretically one may find that the emission coefficient is still significant for small loss-cone angles. However, we must bear in mind that for the case of a very small loss-cone angle the resonance ellipse becomes very small. As a result, an emitted wave would have a rather narrow bandwidth.

According to the present theory, emission of type III bursts occurs only when the energetic electrons are generated at sufficiently high altitudes. The reason is that when the generation takes place at low altitudes, where the loss-cone angle is large, few beam electrons would be reflected. Of course, the threshold

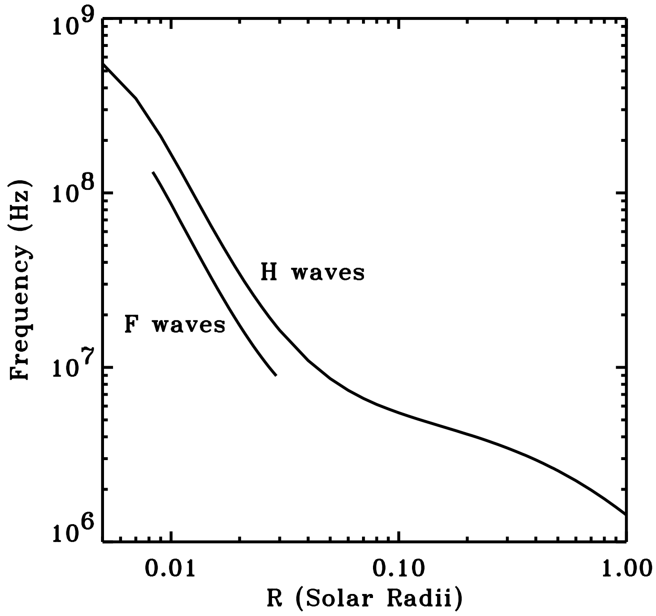

FIG. 8.—True source regions of the emitted F and H components are shown as functions of altitude. Of particular interest are the starting frequencies of the H wave and F wave. It is seen that the H wave can have a starting frequency much higher than that of the F wave. In the present case the former is about 550 MHz, while the latter is around 120 MHz.

altitude depends upon the behavior of the magnetic field in the region of interest. From this conclusion we see why sometimes we see a flare event but do not necessarily observe type III radiation.

In the present theory we have so far neglected O-mode F waves. The reason is, as explained in Wu et al. (2002), that spontaneously emitted O-mode F waves have much lower level than that of the X-mode F waves. However, this does not mean that O-mode waves are in general unimportant. A discussion along this line is therefore necessary. First of all, we must point out that, in a source region where the plasma frequency is lower than the gyrofrequency, it is allowed to have O-mode F waves with frequencies below the gyrofrequency, a situation very different from that of the X-mode F waves. Consequently, a beam of electrons can excite O-mode F waves propagating in opposite directions. However, because the emission coefficient depends on a factor of u_z^2, it may not be significant at low altitudes where the beam momentum is low. Moreover, we also point out that when the electron energy is sufficiently high, the level of spontaneously emitted O-mode F waves may be comparable to that of the X-mode H waves. A downwardly propagating O-mode F wave would be reflected at a low altitude where the local plasma frequency is equal to the wave frequency. These waves may explain the well-known type V emission. Indeed, this argument is similar to that given in Wu et al. (2002). Another relevant point is that the emitted radiation discussed in the present theory would not resonate with the thermal electrons at the second harmonic. As a result, no absorption is expected there. An extensive amount of numerical computation of both X-mode and O-mode growth rates for a broad range parameters is carried out by Chen et al. (2005).

Finally, we must point out that to some extent the proposed scenario is very similar to that for the Earth's auroral kilometric radiation (known as AKR) observationally identified 30 years ago (Gurnett 1974). AKR is explained by a number of theorists on the basis of a cyclotron-maser instability theory (Wu & Lee 1979; Lee et al. 1980; Dusenbery & Lyons 1982; Wu et al. 1982; Melrose et al. 1982; Omidi & Gurnett 1982; Le Queau et al. 1984 and many other authors). Admittedly, we all missed the point that a similar scenario could explain type III solar radio emission.

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APPENDIX

The function G_q in equation (3) is

$$G_q \equiv \frac{\pi}{2}\frac{n_b}{n_0}\frac{\omega_p^2}{\omega_q}\frac{1}{R_q(1+T_q^2)}\left[\frac{1}{2n!}\frac{\omega_q}{\Omega}(K_q \sin\theta + T_q\cos\theta) + \frac{1}{2(n-1)!}\right]^2, \tag{A1}$$

where n_b and n_0 are the number density of the loss-cone electron beam and the background electron inside the density-depletion flux tube, respectively. Other quantities in equation (A1) are defined as (Melrose 1986)

$$R_q = 1 - \frac{\omega_p^2\Omega\tau_q}{2\omega_q(\omega_q+\tau_q\Omega)^2}\left[1 - \frac{qs_q}{(s_q^2+\cos^2\theta)^{1/2}}\frac{\omega_q^2+\omega_p^2}{\omega_q^2-\omega_p^2}\right], \tag{A2}$$

$$K_q = \frac{\omega_p^2\Omega\sin\theta}{(\omega_q^2-\omega_p^2)(\omega_q+\tau_q\Omega)}, \tag{A3}$$

$$T_q = -\frac{\cos\theta}{\tau_q}, \tag{A4}$$

and $\tau_q = -s_q + q(s_q^2+\cos^2\theta)^{1/2}$, with $s_q = \omega_q\Omega\sin^2\theta/[2(\omega_q^2-\omega_p^2)]$. In equations (A2), (A3), and (A4), $\omega_q^2 > \omega_p^2$. The wave mode is designated by q ($q = +1$ for the O-mode, and $q = -1$ for the X-mode).

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