Generation Mechanism of Low Latitude ELF Emissions

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Employing a realistic ionospheric model and suitable energetic electron spectra, intensity and growth rate calculations are done to know the generation mechanism of low latitude ELF emissions. It is found that the soft electrons radiating in the incoherent Cerenkov mode are not responsible for the generation of these emissions. In contrast to this, they are generated in the equatorial plane below \( L = 1.7 \) as a result of cyclotron resonance between whistler mode waves and the inner zone relativistic electrons having energy \( \sim 1-6 \) MeV with their greater probability of occurrence towards lower \( L \)-values.

1 Introduction

The steady noise-like broad band natural electromagnetic waves lying in the frequency range of a few Hz to 3 kHz and generated by wave-particle interaction phenomena occurring in the ionosphere and magnetosphere are generally known as the extremely low frequency (ELF) emissions. These emissions play an important role in the generation of other emissions such as chorus1 and in the precipitation of energetic electrons in the lower region of the ionosphere2. The study of these emissions, therefore, also provides very valuable information regarding the structure and dynamics of the ionosphere and magnetosphere. These emissions have been observed adequately and studied extensively at high and middle latitudes3-7. However, such emissions have been observed and studied rarely at low latitudes. Ondoh and Isono8 have reported the observation of ELF hiss at 2 kHz for the first time in the low latitude ground station of Hirasai (geomag. lat., 26.2° N) in Japan. Ondoh et al.9 have reported the observation of ELF hiss aboard Alouette-2 satellite in the low latitude ionosphere and have indicated the possibility of their generation through incoherent Cerenkov radiation mechanism employing soft electrons with energy below 4 keV in the topside ionosphere. Tsurutani et al.2 have detected ELF hiss below 1 kHz aboard OGO-6 satellite and have argued that the hiss generates in the vicinity of the plasmapause (plasmaspheric hiss) and propagates into the inner zone to be observed there during storm and substorm periods. Recently, Hayakawa and Tanaka10 have reported the observation of ELF hiss (frequency range 1-2.5 kHz and 2-3 kHz) at Moshiri (geomag. lat., 34.3° N) in Japan. They have studied the morphological characteristics of these emissions and have supported the generation and propagation model of Tsurutani et al.2

However, the generation and propagation model of Tsurutani et al.2 fails during quiet periods when strong Landau damping11 prevents the magnetospheric hiss from reaching the inner zone. Further, the pioneering theoretical work of Etcheto et al.6 has stressed the importance of cyclotron resonance in the generation of magnetospheric ELF emissions. The earlier studies, therefore, do not give a clear picture of the generation mechanism of the low latitude ELF emissions. Electromagnetic emissions are generated generally through two mechanisms, viz. incoherent Cerenkov mechanism and cyclotron resonance mechanism. In order to examine which of the two mechanisms is best suited for the low latitude ELF emissions, the intensity, resonant energy and the growth rate calculations are carried out in this paper for these emissions by considering realistic ionospheric model and suitable energetic electron spectra.

2 Ionospheric Model and Expressions Used

In the present calculations, the familiar diffusive equilibrium model12 is employed. This model is represented at a reference level of 400 km by an electron density of \( 1.5 \times 10^5 \) el. cm\(^{-3} \), \( O^+ \) of 95%, He\(^+\) of 4.75%, H\(^+\) of 0.25%, and a temperature of 1000 K. The electron density in this model is taken from Alouette-I satellite observations corresponding to low latitudes, the oxygen and helium densities and temperature are taken from the analysis of incoherent back-scattered spectra gathered over the period 1965-67 (Ref. 13) and the nighttime concentrations of
hydrogen ions are taken from the Injun-III proton whistler analysis\textsuperscript{14}. This nighttime low latitude ionospheric model has been used earlier by a number of workers\textsuperscript{15–18}.

To calculate the intensity of the low latitude ELF emissions, the expression of Mansfield\textsuperscript{19} is considered which has been used previously by a number of workers to interpret VLF emissions at auroral latitudes\textsuperscript{20–22} as well as at low latitudes\textsuperscript{17,18,23}. The expression gives the intensity in W Hz\textsuperscript{-1} per electron. The general Cerenkov condition in a magnetoplasma for emission of a wave at an angle $\theta$ to the geomagnetic field direction is expressed by the relation

$$v_{\parallel} \cos \theta = c / \mu$$

where $v_{\parallel}$ is the component of the particle velocity along the magnetic field direction, $c$ the velocity of light in vacuum and $\mu$ the refractive index of the medium. The value of the angle $\theta$ as obtained from the above relation is substituted in the expressions of $T_{11}$, $T_{13}$ and $T_{33}$ which appear in the power expression of Mansfield\textsuperscript{18}.

The resonant energies for various frequencies of the ELF emissions are calculated from the expression

$$E_{\parallel} = (\gamma_r - 1) m_0 c^2$$

where $m_0$ is the rest mass of electron, and $\gamma_r$ is the relativistic factor to be estimated from the relation

$$\gamma_r^2 - 1 \approx (\Omega_c / \omega_p)^2 (\Omega_e / \omega)(1 + \Omega_H / \omega)$$

where $\omega_p$ the plasma frequency, $\omega$ the wave frequency, $\Omega_c$ the electron gyrofrequency and $\Omega_H$ the proton gyrofrequency.

In order to calculate the growth rate, we follow the general weak diffusion theory of Kennel and Petschek\textsuperscript{24}. According to this theory the expression for the growth rate is given by

$$\gamma = \pi \Omega_e (1 - \omega / \Omega_e)^2 \eta (A - \omega / \Omega_e - \omega)$$

which, in the case of low latitude ELF emissions ($\omega \ll \Omega_e$), reduces to

$$\gamma = \pi \Omega_e \eta A$$

where $\eta$ is the ratio of the density of energetic electrons to that of the thermal electrons and $A$ is the pitch angle anisotropy.

3 Results and Discussion

In order to test whether the incoherent Cerenkov radiation mechanism is responsible for generation of ELF emissions over equator at low latitudes as suggested by Ondoh \textit{et al.}\textsuperscript{9}, the intensity of these emissions (in W Hz\textsuperscript{-1} per electron) is calculated at different $L$-values of 1.55, 1.63 and 1.7 (corresponding maximum equatorial heights being 3500, 4000, and 4459 km, respectively). Energetic electrons having energy 100 eV-10 keV and pitch angle 0° are considered. The calculations are done at different frequencies of 1, 2 and 3 kHz. Since the intensities calculated at the different $L$-values over the equator have nearly the same order of magnitude at the same frequency and energy, the intensities calculated at the $L$-value of 1.63 only are presented in Table 1. The Cerenkov condition for 100 eV electrons is not satisfied and hence the intensities corresponding to these electrons are also not tabulated. It is clear from Table 1 that the intensity is directly proportional to both the frequency of the wave and the energy of the electrons.

The volumes of the flux tubes along the field lines corresponding to the $L$-values of 1.55, 1.63 and 1.7 (each having a cross-section of 1 cm\textsuperscript{2} at 500 km in the ionosphere and extending to the equatorial plane) are then calculated. The calculated volumes of these flux tubes are found to be $1.665 \times 10^9$, $2.132 \times 10^9$ and $2.625 \times 10^9$ cm\textsuperscript{3}, respectively\textsuperscript{16}. In order to determine the densities of the energetic electrons in the flux tubes, an electron energy spectrum for these particles is required. For this purpose, an energetic electron spectrum measured by Hakkila\textsuperscript{25} in the low latitude topside ionosphere is employed. This spectrum gives intense fluxes of $5 \times 10^9$ el./cm\textsuperscript{2} ster sec for 10 eV-10 keV electrons and is suitable for the present calculations. Considering that the particles of energy 1 keV and 10 keV have fluxes of $5 \times 10^9$ el./cm\textsuperscript{2} ster sec, their corresponding densities are found to be 33 and 10.46 cm\textsuperscript{-3}. Now further assuming that the fluxes remain constant along the field lines under consideration, these densities are multiplied with the tube volumes and the intensity calculated in the topside ionosphere to get the intensities in W m\textsuperscript{-2} Hz\textsuperscript{-1} at the base of the corresponding tubes (500 km) in the ionosphere.

The calculated intensities at the $L$-value of 1.63 are found to be between $1.383 \times 10^{-29}$ and $7.801 \times 10^{-27}$ W m\textsuperscript{-2} Hz\textsuperscript{-1}. The intensities calculated in a similar way at the $L$-values of 1.55 and 1.7 are found to be in the range $6.648 \times 10^{-30}$ - $2.780 \times 10^{-27}$ and $2.55 \times 10^{-29}$ - $1.692 \times 10^{-26}$ W m\textsuperscript{-2} Hz\textsuperscript{-1}, respectively. These intensities will be further lowered if the ionospheric losses are taken into account\textsuperscript{16,17}. The peak power fluxes of 2 kHz ELF emissions observed at the low latitude ground station of Hiraiso (geomag.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Calculated intensity (in $10^{-40}$ W Hz\textsuperscript{-1} per electron) for 1 keV and 10 keV electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.965</td>
</tr>
<tr>
<td>1.5</td>
<td>5.109</td>
</tr>
<tr>
<td>2.0</td>
<td>12.940</td>
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<tr>
<td>2.5</td>
<td>3498.0</td>
</tr>
</tbody>
</table>

Table 1—Calculated Intensities in the Topside Ionosphere for 1 keV and 10 keV electrons
The intensity observed aboard Ariel-3 satellite at 3.2 kHz (height 500 km, geomagnetic latitude < 30°) is ~ 10^{-16} \text{ W m}^{-2} \text{ Hz}^{-1} (Ref. 27). The calculated intensity is, therefore, too low to account for the intensity observed both on the ground and aboard satellite. Thus, it is concluded that the generation of ELF emissions at low latitudes cannot be interpreted in terms of incoherent Cerenkov radiation process occurring over the geomagnetic equator.

In contrast, the low latitude ELF emissions may be generated by the cyclotron resonance interaction between the whistler mode waves and the inner zone radiation belt relativistic electrons. To test this, the resonant energy of the involved energetic electrons and the growth rates for these emissions are calculated at different L-values of 1.3, 1.5 and 1.7 in the equatorial plane. It is worthwhile to mention here that the generation region cannot be considered lower than \( L = 1.2 \), because in the lower regions of the ionosphere, electron losses are dominated by atmospheric scattering\(^{28,29}\). The thermal electron densities at the considered L-values are calculated from the diffusive equilibrium model described in Section 2 which are found to be 4.6087 \times 10^3, 2.7055 \times 10^3 and 1.9802 \times 10^3 \text{ el. cm}^{-3}, respectively. These values of densities are used to calculate the corresponding plasma frequencies which are then used to estimate the resonant energies of the involved energetic electrons from Eqs. (2) and (3). The calculated resonant energies are shown in Fig. 1. It is observed that the resonant energies increase as the L-value and the frequency of the wave decrease and are \( \sim 1-6 \text{ MeV} \). To obtain the density of the energetic electrons, the observed intensity versus L-value curves (energy \( > 1 \text{ MeV} \)) given by Katz\(^{20}\) for the inner zone radiation belt are considered. The curves indicate the fluxes of \( 5 \times 10^6, 4 \times 10^6 \) and \( 1.2 \times 10^6 \text{ el. cm}^{-2} \text{ ster} \text{ sec} \) at the L-values of 1.3, 1.5 and 1.7, respectively. Now assuming that 1-6 MeV electrons are involved in the generation of low latitude ELF emissions, the above fluxes are divided by the velocity of these electrons to obtain their densities at the above L-values and found to be \( 2.1 \times 10^{-3}, 1.69 \times 10^{-3} \) and \( 5.17 \times 10^{-4} \text{ el. cm}^{-3} \), respectively. On dividing these densities by the thermal electron densities, the values of \( \eta \) are obtained. The values of the pitch angle anisotropy \( A \) at the above L-values are calculated from the relation\(^{24}\) \( A = \frac{1}{2} \left[ \log_e(1/z_0) \right] \) (\( z_0 \) being the equatorial loss cone angle, mirror height being assumed to be 100 km) and found to be 1.20, 0.70 and 0.53, respectively. Now, by substituting the values of \( \Omega, \eta \) and \( A \) in Eq. (5), the growth rates at different frequency components of the ELF emissions are calculated. Fig. 2 shows the variation of calculated growth rate at 2 kHz with L-value. Nearly the same values of growth rate are obtained for the other frequency components because of the fact that for low latitude ELF emissions \( \omega \ll \Omega_c \). Fig. 2 indicates a significant wave amplification. Thus, the generation of low latitude ELF emissions is explained very well in terms of cyclotron resonance interaction between the whistler mode waves and the inner zone radiation belt relativistic electrons of energy \( \sim 1-6 \text{ MeV} \). Further, since the growth rate increases with the decrease of L-value, the probability of occurrence for these emissions will be higher towards lower L-values.

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References