Generation of VLF hiss and chorus in Jupiter's magnetosphere

(Y-SINGH)

(Geophysical Party No. 20, Oil & Natural Gas Commission, 226, Cathedral Road, CSI building,
Madras 600 086)

Received 24 January 1990; revised 5 November 1990; accepted 5 December 1990

Using the plasma and field parameters corresponding to \( L = 8 \), temporal growth rates of VLF waves have been computed for a non-Maxwellian electron distribution function in the Jovian magnetosphere. It is found that the presence of bi-Maxwellian electron distributions leads the generation of VLF chorus just below the one-half of the electron gyrofrequency and the presence of nonthermal drifted Maxwellian tail leads the instability below one-fourth of the electron gyrofrequency. The computed results are in good agreement with those reported by the Voyager 1 and 2 plasma wave experiments.

1. Introduction

The plasma wave instrument onboard the Voyager spacecraft has returned wealth of information regarding a variety of plasma waves throughout the Jupiter's magnetosphere\(^1\) - \(^5\). A programme of long-term studies of the earth's magnetosphere—a variable plasma wave laboratory—has served as a guide for the interpretation of Jovian plasma wave data based on phenomenological similarities with the terrestrial emissions\(^6\) - \(^9\). These investigations have contributed to our understanding of how Jovian plasma waves are related to the plasma physical processes on a microscopic level and have clearly indicated that these waves have a key role in affecting magnetospheric particle dynamics. Within the Io torus region Scarf et al.\(^1\) tentatively identified a low frequency (\( f < 1 \text{ kHz} \)) electric field noise band as whistler mode hiss and suggested that it could be produced by pitch angle scattered electrons. Subsequently, Scarf et al.\(^2\) and Thorne and Tsurutari\(^10\) qualitatively demonstrated that the pitch angle diffusion rates would cause substantial electron precipitation and also noticed that an intensity peak at higher frequencies (\( f > 10 \text{ kHz} \)) observed near \( 8R_J \) on the Voyager 1 in bound pass might also be whistler mode noise. Coroniti et al.\(^11\) discussed the details of the detected high frequency waves near one-half of the electron gyrofrequency and reported that the signals which have frequencies less than or equal to one-half electron gyrofrequency are banded whistler chorus and just above the one-half electron gyrofrequency the signals are half cyclotron frequency emissions. The existence of these signals allows the presence of fluxes of keV electrons.

In the last decade an enormous amount of detailed information of local particle characteristics has been gathered and it is now evident that many mechanisms operate to produce a complex variety of non-Maxwellian and unstable plasma distribution functions in the Jovian ionized environment\(^12\) - \(^15\). The thermal anisotropy \( \left( \frac{T_\parallel}{T_\perp} > 1 \right) \) is one of the major factors causing instability in the plasma distributions. This anisotropy in turn is caused mainly by (i) inward plasma diffusion and convection with conservation of magnetic moment, (ii) cyclotron and betatron acceleration effects, and (iii) selective pitch angle scattering into the loss cone. It has also become clear in the recent years that the natural plasmas are locally non-Maxwellian in the sense that there are significant peaks and dips in the energy distributions. These fluctuations arise because the solar wind and the ionosphere are more or less two independent sources of warm and cool magnetospheric plasma. The varying gradient drifts selectively remove the trapped particles in the restricted energy ranges from the magnetosphere. They leave residual quasi-trapped distributions with deep flux ripples, collisionless acceleration processes which apparently provide enhanced fluxes at certain energies and, resistive dissipation and heat conduction which contribute to the observed nonthermal tail distributions. Some remarkable examples of non-Maxwellian distribution functions between 5.5 and 8.9 \( R_J \) in the Jovian magnetosphere are described by Scudder et al.\(^13\) similar to those described at the synchronous...
There is strong evidence that the entire electron distribution function can be well adjusted by a superposition of bi-Maxwellian and a drifted Maxwellian\(^{17-20}\). The nonthermal part of the distribution function confirms well with the requirement of power law energy spectrum\(^{21}\).

Recently, Singh and Singh\(^{22}\) have studied in detail the propagation of whistler mode waves through the plasma characterized by double Maxwellian distribution function which consists of thermal and nonthermal tail components in the earth's magnetosphere. In this paper, a theory is proposed to explain the observed VLF hiss and chorus in the Jovian magnetosphere. An analytical expression of normalized growth rate is derived in Section 2. Using the appropriate plasma and field parameters corresponding to \(L = 8\), the normalized growth rate with normalized wave frequency is computed and the results are discussed in Section 3. Finally it is concluded that the results are in good agreement with those reported by the Voyager 1 and 2 spacecrafts.

### 2 Basic theory

The entire electron velocity distribution function is considered to be a superposition of drifted Maxwellian distribution representing the low density beam population and a bi-Maxwellian in a homogeneous, uniform and magnetized plasma,

\[
F_0 = F_1 + F_N \quad ... (1)
\]

where

\[
F_I = N_1 \pi^{-3/2} \alpha_{z,T}^{-1} \alpha_{z,I}^{-1} \exp \left[ -\frac{V_z^2}{\alpha_{z,I}^2} - \frac{V_z^2}{\alpha_{z,T}^2} \right] \quad ... (2)
\]

and

\[
F_N = N_2 \pi^{-3/2} \alpha_{z,N}^{-3} \exp \left[ -\frac{V_z^2}{\alpha_{z,N}^2} - \frac{(V_z - V_h)^2}{\alpha_{z,N}^2} \right] \quad ... (3)
\]

Here \(N_1\) and \(N_2\) are the electron number densities of thermal and beam components respectively where \(N_2 < N_1\) is assumed. \(\alpha_{z,I}\) and \(\alpha_{z,T}\) are the perpendicular and parallel components of the thermal speed of thermal electrons with respect to the magnetic field direction. \(V_z\) and \(V_h\) are the thermal and drift speeds of the beam or drifting Maxwellian electrons respectively. In order to assess the rate of wave growth, a one dimensional model is considered in which the magnetic field \(B_z\) is directed in the positive \(Z\) direction. Assuming the wave propagation as \(\exp[i(kz - \omega t)]\), where \(\omega\) is the angular wave frequency and \(k\) is the propagation constant, the linear whistler mode dispersion equation is obtained with the help of coupled Vlasov-Maxwell equations as,

\[
c^2 k^2 = \left[ \omega R \left\{ A - \frac{1}{k \alpha_{z,T}} Z(\xi) \right\} \right] (A + 1) (\Omega_e - \omega)
\]

\[
- \Omega_e + \omega \_{a}^2 \left( \frac{1}{k \alpha_{z}} \right) Z(\xi)
\]

\[
\ldots \quad (4)
\]

where

\[
\xi = \frac{(\omega - \Omega_e)}{k \alpha_{z,T}}, \quad \xi = \frac{(\omega - \Omega_e - k V_h)}{k \alpha_{z}}, \quad A = \left( \frac{T_e}{T_z} - 1 \right)
\]

and \(\Omega_e\) and \(\omega_{a}\) are cyclotron, thermal electron and nonthermal electron plasma angular frequencies respectively. \(Z(\xi)\) is the general plasma dispersion function as defined by Fried and Conte\(^{23}\). Following the procedure of Singh and Singh\(^{22}\), the expression for the normalized temporal growth rate can be obtained in the limit \(\omega_R \gg \omega_t\) (\(\omega_R\) is the real part of the wave frequency and \(\omega_t\) is the imaginary part) and is written as

\[
\gamma = \frac{\pi^{1/2}}{k} \left( R_1 + R_2 \right)
\]

where

\[
R_1 = \left[ A \right] (1 - x - x) \exp \left[ -\frac{(1 - x)^2}{k^2} \right]
\]

\[
R_2 = \frac{\delta_1}{\alpha_{z}} \left( kV_h - x \right) \exp \left[ -\frac{(1 - x + kV_h)^2}{(k \alpha_{z,N})^2} \right]
\]

\[
P_1 = \left[ \delta_1/(1 - x)^2 \right] \left[ 1 + k^2 P/2(1 - x) \right]
\]

\[
P_2 = \left[ \delta_2/(1 - x + kV_h)^2 \right] \left[ 1 + k^2 Q \alpha_{z,N}^2 \right]
\]

\[
\tilde{P} = \left[ (1 + 2x)/(1 - x) - 2A \right]
\]

\[
Q = (2x - 2kV_h + 1)/(1 - x + kV_h)
\]

\[
\tilde{R} = \left[ 1 + \frac{\delta_1 \alpha_{z}^2}{2(1 - x)^3} \left( A - \frac{x}{1 - x} \right) - \frac{\delta_2 \alpha_{z,N}^2 \alpha_{z,T}^2}{2(1 - x)^3} \right]^{1/2}
\]

\[
\tilde{k} = \left[ x^2 + \frac{\delta_1 \alpha_{z}^2}{(1 - x)} \left( 1 + \frac{N_2}{N_1} \right) \right]^{1/2}
\]

In the absence of tail of beam electrons, Eq. (5) of normalized growth rate reduces to the one obtained by Kennel & Petschek\(^{24}\). The value of \(\gamma > 0\) corresponds to growth of waves and \(\gamma < 0\) corresponds to damping.
3 Results and discussion

In this study, the general behaviour of whistler mode instability is discussed as due to the presence of a non-Maxwellian velocity distribution function which consists of thermal bi-Maxwellian and non-thermal drifted Maxwellian plasma tail in the Jovian magnetosphere. The number density of thermal electrons is used in the range \(1.5 \times 10^9\) to \(1.05 \times 10^9\) m\(^{-3}\) which conforms well with the observations of local plasma density in Io torus by radioastronomy investigation\(^{25}\), and their parallel thermal energy is in the range 50-350 eV as reported by Voyager plasma experiment\(^{13}\). The magnetic field strength is taken to be 800 nT (Ref. 26) which gives an electron gyrofrequency of 22.4 kHz. The number density of non-thermal electrons is taken between 2.8 and 19.6% of the thermal plasma. Although Scudder et al.\(^{13}\) reported this variation at times up to 50% of the thermal plasma with many temporal perturbations. The low energy charged particle investigation on the Voyager spacecraft utilizes a variety of solid state detectors and measured the energetic electrons in the energy range 14 keV-10 MeV and energetic ions in the range 30 keV-150 MeV in several energy intervals with good energy species time and spatial resolution during 5-20 \(R_J\) of the Jovian magnetosphere\(^{27}\). In this study, the energy of beam electrons is used in the range 15-300 keV.

Using appropriate plasma and field parameters corresponding to \(L=8\) as discussed above and expression of growth rate as given in Eq. (5), the normalized growth rate with normalized wave frequency is computed. The computed growth rate variation with normalized wave frequency shows a main peak at a normalized frequency \(< 1\) which is known 'chorus' and is invariably accompanied with a trailing growth at lower frequencies known as 'hiss' (Figs 1-6). Further, it is seen that the presence of nonthermal electrons tail results into a significant change in the normalized growth rate at lower wave frequencies. In Fig. 1, it is shown that the increase of number density of thermal electrons reduces the peak value of the growth rate for chorus. Figure 2 shows that the increase in parallel energy of thermal electrons leads to small increase in the peak value of chorus, whereas the increase in the temperature anisotropy increase the peak value very significantly as shown in Fig. 3. The increase in parallel energy of thermal electrons enhances the peak value of hiss generated due to the presence of nonthermal electrons and shifts it towards higher frequencies whereas growth rate is almost unaffected at lower wave frequencies.

\[
\begin{align*}
N_2 &= 4.2 \times 10^8 \text{ m}^{-3} \\
T_b &= 50 \text{ eV} \\
V_{\parallel 2} &= 100 \\
N_1 &= 1.5 \times 10^9 \text{ m}^{-3} \\
T_a &= 50 \text{ keV} \\
V_{\parallel 1} &= 100 \\
T_{\parallel 1} &= 50 \text{ keV} \\
T_{\perp 1} &= 50 \text{ keV} \\
A &= 0.7 \\
L &= 8
\end{align*}
\]

Fig. 1—Normalized growth rate variation for different number densities of ambient electrons

Fig. 2—Normalized growth rate variation for different thermal velocities of ambient electrons
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Fig. 3—Normalized growth rate variation for different temperature anisotropies of ambient electrons

Fig. 4—Normalized growth rate variation for different number densities of beam electrons

Fig. 5—Normalized growth rate variation for different thermal velocities of beam electrons

Fig. 6—Normalized growth rate variation for different drift velocities of beam electrons
frequencies due to change of temperature anisotropy. The effects of number density, parallel energy and drift velocity of nonthermal electrons are shown in Figs 4, 5 and 6 respectively. It is found that the increase in the number density of nonthermal electrons increases the hiss peak caused by drifting of beam electrons and shifts it towards lower wave frequencies and reduces the peak of chorus caused by temperature anisotropy. The parallel energy of beam electrons produces a similar effect on normalized growth rates as electron number density does. Figure 6 shows the variation of normalized growth rate for different values of drift velocity of beam electrons. It is clear that the lower drift velocity \( V_n \leq \alpha_x f^2 / 2 \) does not generate the hiss at lower frequencies whereas it increases the peak value of chorus. After a critical value \( V_n > \alpha_x f^2 / 2 \) the increase in the drift velocity gives finite growth rate at lower wave frequencies which is consistent with the presence of hiss as measured experimentally aboard Voyager 1 and 2 (Refs 1 and 2). The finite drift velocity of beam electrons opposite to the direction of wave propagation is found to reduce the growth rate of VLF waves in general. It also reduces the peak value of VLF chorus generated due to temperature anisotropy and does not generate the VLF hiss at the low frequencies.

The velocity distribution function with bump in the tail used in this study for accounting the presence of ambient and beam electrons has been used by other workers\(^{19-20}\) to account for the effect of field-aligned current on the VLF emissions. The results obtained in this study compares well with those reported by Kulkarni and Landage\(^{19}\). It is found that these results logically follow the same trend in the absence of drift velocity of beam electrons along the direction of wave propagation. However, in the presence of finite drift velocity along the direction of wave propagation plays an important role in increasing the general level of VLF hiss and in increasing the peak value of VLF Chorus generated by temperature anisotropy.

Thus, from the present study it is concluded that the presence of thermal bi-Maxwellian electrons are responsible for the generation of VLF chorus at high frequencies below one-half of the electron gyrofrequency, whereas the presence of drifting Maxwellian electrons along the direction of wave propagation are responsible for a wide range of unstable low frequency hiss emissions below one-fourth of the electron gyrofrequency. The results compare well with the earlier results of Coroniti \textit{et al.}\(^{13}\), and are also in good agreement with those reported by Voyager spacecrafts.

Acknowledgement

This work was carried out during the period when the author was working as a Visiting Scientist in Swedish Institute of Space Physics, Kiruna, Sweden, in 1988. The author is thankful to Prof. Bengt Hultqvist, Director, Swedish Institute of Space Physics, for his constructive comments on the manuscript and for providing computer facilities. Thanks are also due to Prof. R N Singh of Banaras Hindu University for his continuing interest in this work. He also wishes to express his gratitude to the General Manager (E), Oil & natural gas commission, Madras, for permitting him to get this work published.

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