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ABSTRACT

Because the particles and electric fields associated with inverted-V electron streams do not have the characteristics expected for acceleration by a quasistatic potential difference, the possibility that the electrons are stochastically accelerated by waves is investigated. It is demonstrated that the lower hybrid waves seen on auroral field lines have the right properties to account for the electron acceleration. It is further shown that the lower hybrid wave power measured on auroral field lines can be generated by the streaming ions observed at the boundary of the plasma sheet, and that this wave power is sufficient to account for the electron power observed close to the atmosphere.

INTRODUCTION

In this paper we describe in detail the model outlined by Bingham et al [1984] in which it was proposed that the stream of electrons that are associated with discrete aurorae are accelerated by electrostatic waves.

The first direct measurements of the electrons that produced a discrete aurora were made by McIlwain [1960], who after careful examination of the data, deduced that the electron spectrum responsible for producing a bright active auroral arc was more sharply peaked in intensity than a Maxwellian. The spectrum was described as consisting of nearly mon-energetic electrons with about 6 keV energy. The sharpness of the peak argued against it having been generated by a statistical type process, and acceleration by electric fields parallel to the earth's magnetic field was suggested as a possible cause. This was followed by the work of Albert [1967], Evans [1968], and Hoffmann and Evans [1968], who, in order to account for their observations of "near-monoenergetic electrons" and field aligned electrons, suggested that the electrons traversed a magnetic-field-aligned potential difference which accelerated them to energies of a few keV. This interpretation has since become almost a tenet of auroral physics.

Observations of perpendicular electric fields [Mozer et al 1977; Swift, 1978] were at first thought to be positive proof of particle acceleration by field aligned electric fields. However there are some problems with this interpretation. The electric fields measured do not have the spatial structure that is necessary to account for inverted-V electron streams. The latitudinal widths of the field structures are within the range 0.001-0.1 degrees [Mozer, 1981] whilst, the electron streams that Frank and Ackerson [1971] called inverted-V's extend in latitude for about 0.5-3 degrees. Swift [1978] has in fact pointed out the difficulties encountered when attempting to account for the larger-scale phenomena by invoking processes that might maintain field-aligned potential differences. To account for the decoupling of the assumed magnetospheric electric fields from the observed ionospheric fields, "double sided" shocks (ie large electric fields of opposite polarity separated by a field reversal) are necessary (Markland 1984; Hall, 1985). However, most shocks are "single-sided" without the required field reversal (Mozer [1981]). In the evening sector for the auroral oval where most shocks are observed, the predicted potential difference between the magnetosphere and ionosphere would need to be on average about 5 kV in the core of inverted -V's Liu and Hoffmann [1979], Markland [1984]. On average shock electric fields are about $100 mVm^{-1}$ [Bennett et al 1983], and shock latitudinal widths are $<<0.1^{o}$ [Mozer 1981] yielding potential differences << 3kV. Occasionally shock potential differences of up to 13 kV have been reported [Temerin et al, 1981], but even in these cases the shock width ($\sim 0.15^{o}$ invarient latitude) is much less than the widths of the majority of inverted -V's. In addition, Mozer [1981] shows that when examined with the highest resolution some of the larger shocks which appear to extend for 0.1 degrees of latitude, are in fact not continuous in latitude, but are composed of a series of electric field "spikes" that typically have widths of 0.01 degrees. In fact these observations suggest to us the possibility that these large, latitudionally-narrow, perpendicular electric fields, rather than being the signature of the large scale equipotential distribution that would be necessary to account for the streams of accelerated electrons, may simply be the temporal fluctuations in electric field that are to be expected in a turbulent plasma region that is traversed by the downstreaming electrons of inverted V's, upgoing ion beams [Mizera et al 1981], and ion conics [Sharp et al, 1977] and counterstreaming electrons [Sharp et al 1980]. This possibility appears to be well substantiated by the calculations of Singh [1984] and Thiemann et al, [1984], who show that for the plasma on auroral field lines, although certain combinations of particle populations could produce the charge separation necessary to account for the electric fields observed at $\sim 1 R_E$ altitude by spacecraft such as S3-3, the charge separation would only persist for milli-seconds rather than the 10's of minutes necessary to account for the production of inverted-V electron streams.

The auroral particle observations that have been made since 1968 have led to the realization that the electron distributions cannot be accounted for by invoking a process as straightforward as one in which all electrons traverse the same potential difference [O'Brien, 1970; Whalen and McDiarmid 1972]. It was pointed out by Hall and Bryant [1974] that the monotonic, rather than stepped, nature of the electron angular distributions, and the shape of the energy spectrum peak, which is too broad for the electrons to be described as "mono-energetic", indicated a stochastic acceleration process. To account for the wide range of energies that exhibit field alignment, and the wide range of angles over which field alignment extends, Hall and Bryant [1974] introduced the possibility that the accelerating electric field was essentially a time-varying phenomenon, with major fluctuations on time scales of milli-seconds or less. A wave particle interaction process was suggested by Bryant et al., [1978] as the mechanism, although no details of the waves were given. In order to accommodate another common feature of the spectrum - the rise in "temperature" of the high-energy tail with increasing peak energy [Burch et al., 1976, Bryant, 1981] - the degree of acceleration is required to be energy dependent as well as time varying. Bryant [1983] has summarised the discrepancies between the observed electron distributions and those effected for acceleration through a potential difference. Wave-particle interactions have been invoked to account for some of these discrepancies, such as the flatness of the peak on its low energy side [Bryant et al 1978, Lotko and Maggs, 1979, Johnstone, 1980, Maggs and Lotko, 1981, Kaufmann and Ludlow, 1981]; for the flattening of the peak 1979]; and multiple peaks [Hoffmann and Liu, 1981, Arnoldy, 1981].

The conclusions drawn from particle observations that the acceleration mechanism is stochastic and energy dependent has led authors such as Bryant [1978], Whalen and Daly [1979], and Hall [1980] to consider the possibility that the electrons are stochastically accelerated by plasma waves. Kaplan and Tsytovich [1973] have shown that interactions between electrostatic plasma waves and electrons can be very efficient in accelerating electrons to produce non-thermal tails. The effectiveness of electrostatic waves for accelerating electrons has been recognised during the search for current drivers in Tokamak fusion-devices [Boyd et al, 1976].

In this paper we will consider the possibility of electron acceleration by lower-hybrid plasma waves, which are observed to be very intense on auroral field lines Scarf et al [1973]. Lin and Hoffman [1979] have found that inverted-V electron streams on auroral field lines are associated with regions of low frequency turbulence as extensive as the electron streams [Temerin, 1981] rather than with electrostatic shocks. Figure 6 in the paper by Gurnett and Frank [1977] shows that the maximum wave energy resides at frequencies close to the lower hybrid frequency. Scarf et al [1973,1975], using results obtained from Ogo 5 found that the spectrum peaked near the lower-hybrid frequency with a normalized energy density of 10^{-4}-10^{-3} corresponding to electric field strengths between 0.2 - 0.5 Vm^{-1}. The most intense measurements were seen in the region of steep gradients which corresponds to the boundary between the plasma sheet and tail lobes. Bryant et al [1972] first demonstrated that the electron streams associated with discrete aurora were formed at this boundary. this was confirmed by the measurements reported in Bryant et al [1973]. Further confirmation has been provided by the work of Winningham et al [1975] who have shown that diffuse aurora is the footprint on the atmosphere of particles precipitating from the plasma sheet, and that discrete aurora is normally located at the poleward boundary of diffuse aurora. Measurements at the plasma sheet boundary at altitudes of 10-20 R_E have shown that the boundary is not a sudden transition from plasma sheet plasma to magnetotail plasma, but that the plasma sheet contains a boundary layer within which ions stream towards the earth [Decoster and Frank 1979] and highly-structured electron streams occur [Parks et al, 1977]. Lyons and Evans [1984] have demonstrated that the ion streams are associated with the production of discrete aurora.

Lower hybrid waves can be driven unstable by a number of free energy sources. Differential electron-ion drift, cross field currents due to density, temperature and magnetic field gradients, $\underline{E} \times \underline{B}_o$ drift ion loss-cone distributions with a positive value of $\partial f_\perp/\partial v_\perp$ and momentum coupling between interpenetrating plasmas. The most promising free energy source is the earthward streaming ion flow in the boundary plasma sheet [Decoster and Frank, 1979]. The observed power carried by the ion stream at 20 R_E is 2 orders of magnitude higher than that carried by the electrons associated with discrete aurora, just above the atmosphere [Hall et al, 1984]. The process can be considered as a continuous transfer of ion power via the waves to the electrons. The wave power observed at any point is then an equilibrium level between production by the ions and loss to the electrons.

In this paper we calculate growth rates for the waves by the various processes and the saturation level expected.

A quasi-linear theory of wave-particle interactions is then used to describe the acceleration of the tail of the electron distribution function, to calculate an effective tail temperature, number of particles in the tail together with the length of the accelerating region.

LOWER-HYBRID WAVES

It is well known [Kaplan and Tsytovich 1973] that the development of nonthermal tails by stochastic acceleration requires high phase velocities in at least one direction. Lower-hybrid waves have phase velocities along the field lines ranging from just above the electron thermal velocity (V_{TE}) to greater than the speed of light. In laboratory plasmas lower-hybrid waves have been shown to be extremely effective in accelerating electrons along magnetic field lines and in producing high energy tails in the electron distribution function [Boyd et al 1976]. Numerical simulations by McBride et al [1976] and Tanaka and Papdopoulos [1983] show how large field strengths in the lower hybrid mode are generated and how effective these waves are in forming high energy tails. A number of laboratory experiments using ion beams injected along [Ioffe 1961] and perpendicular to the magnetic field [Barrett 1972] demonstrate the role the ion beams play in generating the waves and consequently accelerating electrons.

The dispersion relation for electrostatic waves in a magnetized plasma is [Stix 1962]

$$1 + \frac{k_\perp^2}{k^2}\frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{k_\parallel^2}{k^2}\frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{pi}^2}{\omega^2} = 0 \qquad \ldots.(1)$$

where $k_\perp$ and $k_\parallel$ are the perpendicular and parallel components of the wavenumber with respect to the ambient magnetic field B_o and $k^2 = k_\perp^2 + k_\parallel^2$, $\omega_{ce,i} = eB_o/m_{e,i}$ are the electron (ion) angular gyrofrequencies and $\omega_{pe} = (n_o e^2/m_e \epsilon_o)^{\frac{1}{2}}$ is the plasma angular frequency. For $k_\parallel^2 \ll k^2$ solutions to (1) are called the lower hybrid frequency.

Their frequency is given by:-

$$\omega = \omega_{LH}\left[1 + (k_\parallel/k)^2(m_i/m_e)\right]^{\frac{1}{2}} \qquad \ldots.(2)$$

where $\omega_{LH} = \omega_{pi}/(1 + \omega_{pe}^2/\omega_{ce}^2)^{\frac{1}{2}}$ is the lower hybrid resonance frequency.

These waves have k nearly perpendicular to B_o, there is however an electric field component, and wavenumber $k_\parallel \lesssim (m_e/m_i)^{\frac{1}{2}} k$ parallel to B_o. The group velocities parallel and perpendicular to the magnetic field can be obtained from (2) and are given by:-

$$v_{g\parallel} = \frac{\omega_{LH}}{k}\left\{1 - \frac{k_\parallel^2}{k^2}\right\}\beta$$

$$v_{g\perp} = -\frac{\omega_{LH}}{k}\,\frac{k_\parallel k_\perp}{k^2}\,\beta \qquad -\ (3)$$

$$\beta = \frac{k_\parallel}{k}\,\frac{m_i}{m_e}\left\{1 + \frac{k_\parallel^2}{k^2}\frac{m_i}{m_e}\right\}^{-\frac{1}{2}}$$

From equation (3) and using the condition $k_\parallel^2 \ll k^2$ we obtain the ratio $v_{g\parallel}/v_{g\perp} \simeq -k^2/k_\parallel k_\perp$ it follows that $v_{g\parallel} \gg |v_{g\perp}|$ therefore most of the energy flows parallel to the magnetic field. The phase velocity along the field is given by $v_{ph\parallel} = \omega/k_\parallel$. Using the relation $k_\parallel \lesssim (m_e/m_i)^{\frac{1}{2}} k$ where $k = \omega/c_s$ and c_s is the ion acoustic velocity, k is Boltzmann's constant, T_e, are the electron, ion temperatures respectively we find that $v_{ph\parallel} \gtrsim c_s(m_i/m_e)^{\frac{1}{2}}$, ie $v_{ph\parallel} \gtrsim v_{Te}$. Thus the phase velocity along the field line is greater than the electron thermal velocity. Characteristics of lower-hybrid waves are shown in Fig. 1.

The range of observed frequencies in the auroral zone obtained by S3-3 satellite is plotted in fig 2 Gurnett and Frank [1977]. In the acceleration region which is at altitudes greater than 6000 km the waves have a broad range of frequencies, noting that in this region the expression for the frequency of the waves in a hydrogen plasma is:-

$$f_{LH} = 0.2\, n_o^{\frac{1}{2}}\ kHz \qquad \ldots\ldots(4)$$

where n_o is the mean electron density/cm^3. In the boundary of the plasma sheet there is a broad range of requencies indicating a broad range of parallel phase velocities which can resonate with the electrons and effectively accelerate them.

EXCITATION AND GROWTH RATES

As already noted there are a number of free energy sources on auroral field lines which can generate non-thermal levels of lower-hybrid waves. All the sources ultimately derive their power from the solar wind. One model which transfers the energy from the solar wind to the magnetosphere uses magnetic-field re-connection [see review by Galeev, 1982]. The interaction between the solar wind and the magnetosphere compresses the plasma sheet transversely, the tail then narrows leading to the tearing instability and the formation of a re-connection point. This in turn leads to enhanced particle flows [Decoste and Frank, 1979; Frank et al 1976; Hones et al; 1972] with the ions convecting earthwards and carrying the bulk of the energy. As the plasma sheet is compressed the magnetic field increases leading to the enhancement of temperature and density gradients between the plasma sheet and tail lobes. These conditions produce several mechanisms already noted above which can drive the lower-hybrid waves unstable namely differential electron-ion drift, $\underline{E} \times \underline{B}_o$ drift, cross field currents due to density, temperature and magnetic field gradients and also loss cone type distributions on auroral field lines.

Various names are given to the processes which result in the growth of the waves. If gradients drive the instability, the process is known as the lower hybrid drift instability, if ion convection is the driver it is called the modified two-stream instability. In both cases there is a threshold requirement of $v_d > v_{Ti}$ where v_d is the electron ion relative drift speed and $v_{Ti}\ (=(kT_i/m_i)^{\frac{1}{2}})$ is the ion thermal speed.

In constructing a model from wave growth and electron acceleration we will concentrate on the streaming ions in the Geomagnetic tail [Decoste and Frank, 1979]. The acceleration mechanism then consists of excitation, by the streaming ions, of lower hybrid waves which transfer their energy to the electrons by Cherenkov resonance.

The streaming ions can be regarded as the free energy source from which the lower hybrid waves are excited by an instability which is driven by either a cross field current or by an ion loss-cone distribution [Mikhalovskii 1974]. The first of the two mechanisms is called the modified two stream instability.

MODIFIED TWO-STREAM INSTABILITY

The modified two-stream instability is described by the dispersion relation [McBridge et al 1972].

$$\epsilon(\omega, \underline{k}) = 1 + (2\omega_{pe}^2/k^2 v_{Te}^2)\left[1 + \zeta_e Z(\zeta_e) I_o(\lambda) e^{-\lambda}\right] + (2\omega_{pi}^2/k^2 v_{Ti}^2)\left[1 + \zeta_i Z(\zeta_i)\right] = 0 \qquad -(5)$$

where $\zeta_e = \omega/k_{\parallel} v_{Te}$, $\zeta_i = (\omega - \underline{k}.v_D)/k v_{Ti}$, $k_{\parallel} = k\cos\theta$, $Z(\zeta)$ is the plasma dispersion function (Fried, & Conte, 1962) and $I_o(\lambda)$ is the zeroth order bessel function with $\lambda = k^2 v_{Te}^2 \sin^2\theta / 2\omega_{ce}^2$. In the fluid approximation where resonant particles are unimportant equation (5) reduces to the following simplified dispersion relation

$$1 + k_{\perp}^2 \omega_{pe}^2 / k^2 \omega_{ce}^2 - \omega_{pi}^2/(\omega - \underline{k}\cdot v_D)^2 - k_{\parallel}^2 \omega_{pe}^2 / k^2 \omega^2 = 0 \qquad -(6)$$

which describes modes for which $k v_{Te}/\omega_{ce} \ll 1$, $k v_{Ti} < |\omega - \underline{k}\cdot\underline{v}_D|$ and $k_{\parallel} v_{Te} < \omega$. Equation (6) is similar to the two-stream or Buneman instability dispersion relation (Krall and Trivelpiece, 1973) but is valid for particle drift velocities much less than the electron thermal velocity.

The Term $k_{\perp}^2 \omega_{pe}^2 / k^2 \omega_{ce}^2$ is due to the adiabatic polarization drift of electrons across the magnetic field. The term $k_{\parallel}^2 \omega_{pe}^2 / k^2 \omega^2$ arises because the electrons are free to accelerate under an applied force only along the magnetic field, with the electrons behaving as if they had an effective mass $m_{e(eff)} \simeq k^2 m_e / k_{\parallel}^2$ which is large for $k^2/k_{\parallel}^2 \gg 1$. By writing equation (6) in the following form

$$\left[(\omega^2 - \omega_{LH}^2)\right]\left[(\omega - k_{\perp} v_D)^2 - k_{\parallel}^2 m_i / k^2 m_e \omega_{LH}^2\right] = \frac{m_i}{m_e} \frac{k_{\parallel}^2}{k^2} \omega_{LH}^4 \qquad -(7)$$

where $\omega_{LH} = \omega_{pi}/(1 + \omega_{pe}^2/\omega_{ce}^2)^{\frac{1}{2}}$ we can identify the two waves which couple to produce the modified two stream instability. They are $\omega = \omega_{LH}$ (the lower hybrid mode) and $\omega = k_{\perp} v_D - (k_{\parallel}/k)(m_i/m_e)^{\frac{1}{2}} \omega_{LH}$ (the Doppler-shifted electron mode). For $\omega_{pe} < \omega_{ce}$ which is the situation in the auroral zone the electron mode is just the Doppler-shifted electron plasma oscillation propagating almost perpendicular to B_o with frequency $\omega \simeq k_y v_D - (k_{\parallel}/k)\omega_{pe}$. In this system the lower hybrid mode is the positive energy wave while the Doppler-shifted electron mode is a negative-energy wave. Equation (7) can be solved analytically by writing $\omega = \omega' + \frac{1}{2} \underline{k}.\underline{v}_D$ to give growth rates which agree very well with the numerical solution of equation (5) shown in figure 3. The solution of (7) is

$$\gamma_{g(max)} = \frac{1}{2} \omega_{pi}/(1 + \omega_{pe}^2/\omega_{ce}^2)^{\frac{1}{2}} \simeq \frac{1}{2} \omega_{LH} \qquad \ldots\ldots(8)$$

for a wave number $k \simeq \sqrt{3}\,\omega_{LH}/v_D$ and real frequency $Re\omega = \sqrt{3}\omega_{LH}/2$. The modified two-stream instability occurs for $k_{\parallel}/k \simeq (m_e/m_i)^{\frac{1}{2}}$ such that the wave propagates at an angle of about 1.4^o with respect to the magnetic field. As $k_{\parallel}/k$ increases, the lower hybrid mode no longer couples to the Doppler shifted-electron mode and the instability develops into the ion acoustic instability. Numerical solutions of equation (5) for conditions found in the auroral zones where $\omega_{pe} < \omega_{ce}$ and $T_e \ngtr T_i$ are shown in figure 3. An important consequence of this instability as already pointed out by Barrett et al (1972) is that the instability is insensitive to the electron-ion temperature ratio T_e/T_i, and can take place even if $T_e < T_i$, which limits other electrostatic instabilities, such as the ion-acoustic instability on auroral field lines. the reason the modified two-stream instability can exist for $T_e \leq T_i$ is due to the finite or cut-off value of $Re\omega$ as $k_{\parallel}/k \to 0$. This ensures that the phase velocity of the wave is always greater than the bulk thermal velocity of the ions preventing strong Landau damping. This is even the case when $T_i \gg T_e$. In the auroral zone where the plasma density $n_o \simeq 10cm^{-3}$ the maximum growth rate is $\gamma_{gmax} \simeq 2 \times 10^3\ s^{-1}$ and the time required for 10 e-foldings is of the order of 5×10^{-3} sec this corresponds to a distance L of about 300-1000km along the field lines for waves with phase velocity three times the thermal velocity. The effect of the instability is to heat the ions primarily in the perpendicular direction and accelerate the electrons along the field lines forming a high energy tail. Recent particle in cell simulations of the modified two stream instability by Tanaka and Papadopolous (1983) confirm the threshold and growth rates given by the linear theory. They also show that 60% of an initial ion-stream energy is transferred via lower-hybrid waves to electrons producing a high energy tail extending to about $7V_{Te}$. Their results demonstrate the efficiency in transferring energy from an ion stream to electrons by the modified two stream instability.

ION LOSS-CONE INSTABILITY

Another important mechanism which can transfer the kinetic energy of the ion-stream flowing earthward from the tail to lower-hybrid waves is the electrostatic ion loss-cone instability (Rosenbluth & Post 1965). A dominant characteristic of the ion distributions in the auroral zone is a loss cone type distribution) with a positive value $\partial f_i(v_\perp)/\partial v_\perp$ where

$f_i(v_\perp)$ is the ion distribution function after integration over the parallel velocity. The gyrating beam of ions transfers perpendicular energy from their gyro motion to lower hybrid waves through Landau resonance on the positive slope of the distribution. This instability is similar to the modified two stream instability with a beam type distribution. Both excite the same mode the lower-hybrid mode with the frequency and wavelength satisfying the following inequalities.

$$\omega_{ci} \ll \omega \ll \omega_{ce} \quad , \quad Im\,\omega \gg \omega_{ci}$$

$$k_\perp v_{Te}/\omega_{ce} \ll 1 \ll k_\perp v_{Ti}/\omega_{ci} \quad \text{and} \quad k_\parallel \ll k_\perp$$

where $\rho_{re,i}$ is the electron, ion gyroradius. These assumptions are appropriate for plasmas of moderate densities with $\omega_{pi} \gg \omega_{ci}$.

When these inequalities are satisified we can neglect the influence of the magnetic field on the ion motion. The instability is described by the kinetic equations for ions and electrons together with Poissons equation.

$$\left(\frac{\partial}{\partial t} + \underline{v}.\underline{\nabla} - \frac{e}{m_e}\underline{\nabla}\phi.\frac{\partial}{\partial \underline{v}}\right) f_i(\underline{x},\underline{v},t) = 0 \qquad -(9)$$

$$\left(\frac{\partial}{\partial t} + \underline{v}.\underline{\nabla} - \frac{e}{m_e}\left(\underline{\nabla}\phi + \underline{v}\times\underline{B}_o\right)\right) f_e(\underline{x},\underline{v},t) = 0 \qquad -(10)$$

$$\underline{\nabla}.\underline{E} = -\frac{1}{\epsilon_o}\sum_{j=i,e} e_j \int f_i(\underline{x},\underline{v},t)\,d^3v \qquad -(11)$$

where $\underline{E} = -\nabla\phi$ and ϕ is assumed to have the space-time dependence $[\phi \sim \exp i\,(\omega t + k_\parallel z + k_\perp x)]$. In the linear approximation equations (9)-(11) reduce to the dispersion relation for the electrostatic lower-hybrid mode given by

$$\epsilon(\omega,\underline{k}) = 1 + \omega_{pe}^2/\omega_{ce}^2 - \omega_{pe}^2 k_\parallel^2/\omega^2 k^2 + \frac{\omega_{pi}^2}{k^2}\int \frac{\underline{k}\cdot\partial f_i/\partial \underline{v}}{\omega - \underline{k}\cdot\underline{v} + io}\, d^3v \qquad -(12)$$

In deriving equation (12) we have assumed that the perpendicular wavelength must be larger than the electron gyroradius $k_\perp \rho_{re} \ll 1$ and the parallel phase velocity should be larger than the electron thermal velocity, this assumption is commonly referred to as the cold plasma approximation. The growth rate and frequency of the unstable modes can be obtained from the equations

$$\gamma_g = \mathrm{Im}\,\epsilon(\omega,\underline{k}) \Big/ \frac{\partial \mathrm{Re}\,\epsilon(\omega,k)}{\partial \omega_k} \qquad -(13)$$

To solve (13) we must carry out the ion integrals in equation (12). Defining $\int dv_{i\parallel} f_i(v_{i\perp}^2, v_{i\parallel}^2) = f_\perp(v_\perp^2)/\pi$ and integrating over the parallel velocities the dispersion relation now becomes (Rosenbluth and Post 1905)

$$\omega_{pe}^2/\omega_{ce}^2 + 1 = \frac{\omega_{pe}^2}{\omega^2}\frac{k_\parallel^2}{k^2} + \frac{\omega_{pi}^2}{k^2}\int dv_\perp \frac{\partial f_\perp(v_\perp^2)}{\partial v_\perp} \frac{\omega}{(\omega^2 - k_\perp^2 v_\perp^2)^{1/2}} \qquad -(14)$$

Rosenbluth and Post (1965) have shown that this dispersion relation is unstable for loss cone type distribution functions with a positive value of $\partial f_{i\perp}(v_\perp^2)/\partial v_\perp$ only for $k_\parallel$ finite. The fastest growing waves have frequencies and growth rate given by

$$\mathrm{Im}\,\omega = \gamma_g \simeq \omega_{LH} \qquad -(15)$$

$$\mathrm{Re}\,\omega \simeq \omega_{LH}$$

$$\text{for } k_\parallel/k_\perp \approx (m_e/m_i)^{\frac{1}{2}}$$

The physical nature of this instability is very similar to the two-stream fluid instability discussed previously. The free energy for this instability comes from the perpendicular gyromotion of the ions. The general effect of the instability would be to take energy from the perpendicular energy of the ions pushing them into the loss cone. This instability is convective in nature and therefore it is important to determine the exponentation length along the field lines. Solving equation (14) for the growth length at a given real ω yields

$$k_\parallel^2 = k^2\left[\omega^2(\omega_{pe}^2+\omega_{ce}^2)/\omega_{pe}^2\omega_{ce}^2 - (m_e/m_i)\,y^2 F(y)\right] \qquad -(16)$$

$$\text{where } F(y) = -2\int_0^\infty dx\,\frac{\partial\psi}{\partial x}\,\frac{1}{(1-x/y^2)^{\frac{1}{2}}}, \quad y=\omega^2/2k_\perp^2 v_{Te}^2,$$

$$x = v_\perp^2/2v_{Ti}^2 \quad \text{and} \quad \psi \simeq 2v_{Ti}^2 f_{i\perp}(v_{i\perp})$$

Taking the square root and expanding equation (16) using the condition $k^2 v_{Ti}^2 > \omega_{pi}^2$ yields the following.

$$k^2 = k\left[\omega(\omega_{pe}^2+\omega_{ce}^2)^{\frac{1}{2}}/\omega_{pe}\omega_{ce}\right] - \tfrac{1}{4}(m_e/m_i)\,y\,F(y)\,\omega_{pe}\omega_{ce}/(\omega_{pe}^2+\omega_{ce}^2)^{\frac{1}{2}}v_{Ti}^2 \qquad -(17)$$

The spatial growth rate is obtained from the negative imaginary part of equation (17) ie the negative imaginary part of yF(y). Rosenbluth and Post (1972) analysed the function yF(y) for a distribution function expected in mirror magnetic fields namely

$$f_{i\perp} = (v_\perp^2 - v_\parallel^2)\exp(-m_i v_\perp^2/2kT_i) \qquad \text{for } v_\perp > |v_\parallel| \qquad -(18)$$

$$f_{i\perp} = 0 \qquad \text{for } v_\perp < |v_\parallel| \qquad -(19)$$

Using this function in equation (17) the fastest spatial growth along the field is found to be

$$k_{\parallel(\text{growth})} \simeq 0.1\,(m_e/m_i)^{\frac{1}{2}}\,\omega_{pi}/v_{Ti}\,(1+\omega_{pe}^2/\omega_{ce}^2)^{\frac{1}{2}} \qquad -(20)$$

for a real frequency equal to the lower-hybrid frequency. This corresponds to an exponentiation length

$$L \approx 500\,(1+\omega_{pe}^2/\omega_{ce}^2)^{\frac{1}{2}}\,v_{Ti}/\omega_{pi} \qquad -(21)$$

In the auroral zone this length is about 350 km. For more extreme distributions this length may be much less.

SATURATION LEVEL

So far we have discussed the instabilities which could be responsible for the generation of lower-hybrid waves. To estimate the wave level expected from such instabilities we have to consider the saturation mechanism. An important process common to both instabilities is the transfer of a substantial part of the kinetic energy in the ions to lower-hybrid waves which accelerate a large number of electrons in the tail of the distribution function. The equilibrium level expected when the system is marginally stable ie when their is a balance between production and loss due to accelerating electrons, can be obtained from considering specific saturation mechanisms. Simultations by McBride et al (1972) and Tanaka et al (1983) show that wave growth ceases after ion trapping which leads to a nonlinear frequency shift increasing the parallel phase velocity of the wave which stays in phase with the electron for a much longer period of time increasing the efficiency of the acceleration process. Analytically the waves are found to saturate at an energy density given by

$$W_{LH}/n_o k T_e \simeq 0.05\left(1+\omega_{pe}^2/\omega_{ce}^2\right) \qquad (22)$$

where $W_{LH}\ \left(=\frac{1}{2}\epsilon_0|E|^2\right)$ is the energy density of the lower hybrid wave with an electric field E, and n_o is the plasma density. On auroral field lines where $\omega_{ce} > \omega_{pe}$ the saturation level for the waves given by equation (2) is 5×10^{-2}. This value is to be compared to experimental values of the normalized energy density of 10^{-3}-10^{-4} obtained by Scarf et al (1973, 1975) using results from OGO 5. These experimental values correspond to electric field strengths of between 0.2-0.5 Vm^{-1}, which correspond to power fluxes of 0.10 mW/m^2 at $3R_e$.

STATISTICAL ACCELERATION OF ELECTRONS BY LOWER HYBRID TURBULENCE

When a microinstability develops, fluctuating fields generated by the instability scatter plasma particles and cause diffusion of the velocity distrubution function. If the spectrum of the fluctating fields is characterized by sufficiently small values of the parallel wavenumber $k_{\parallel}$ (ie the component of $\underline{k}\parallel$ to $\underline{B}_o$) such that the phase velocity of the wave is greater than the electron thermal speed, then the waves only resonate with electrons moving with velocities greater than the thermal velocity path along the magnetic field which can be accelerated to higher velocities. We have already demonstrated that lower-hybrid waves can be generated on auroral field lines by a number of instabilities and they have large phase velocities along the field making them suitable waves transfer momentum to the high velocity tail of the electron velocity distribution function via Landau damping.

The statistical acceleration of electrons in the tail of the distribution function due to the resonant interaction with high phase velocity along the field can easily be demonstrated by solving the one dimensional quasi-linear diffusion equation (Davidson 1972).

$$\frac{\partial f_e}{\partial t} = \frac{\partial}{\partial v_{\parallel}} D_{\parallel} \frac{\partial f_e}{\partial v_{\parallel}} \qquad -(23)$$

where f_e is the electron distribution function, and $D_{\parallel}$ is the quasi-linear diffusion operator resulting from the Landau wave-particle interaction, $D_{\parallel} = |\Delta v|^2/\tau$, where Δv is the change in velocity of the particle due to wave particle interaction in time τ. Lin et al (1982) have shown that

$$D_{\parallel} = 16\pi^2 \frac{e^2}{m_e^2} \frac{k_{\parallel}}{\omega} \epsilon_{k_{\parallel}} \qquad -(24)$$

where $\epsilon_{k\parallel}$ is the wave energy density per unit wavenumber

$$\frac{1}{2}\epsilon_0 E^2_{\parallel rms} = \int_0^\infty dk_{\parallel}\, \epsilon_{k_{\parallel}}$$

where $E_{\parallel rms}$ is the rms of the applied lower-hybrid field. For an acceleration region of finite length the effective range of $k_{\parallel}$ is

$$k_m \leq k_{\parallel} \leq k_0 \qquad (25)$$

where k_m is determined by the medium length, and k_0 is determined by the strong Landau damping that takes place for $k_{\parallel} \approx \omega_{LH}/2v_{Te}$.
The total wave energy density is thus

$$W_{LH} = (k_0 - k_m)\epsilon_k \simeq k_0 \epsilon_k \qquad (26)$$

Substituting equation (24) into equation (23) and integrating it can be shown that the asymtotic solution is given by

$$f_e = \frac{n_0}{\sqrt{4\pi(D_{\parallel} t_0)}} \exp\left(-v_{\parallel}^2/4D_{\parallel} t_0\right) \qquad -(27)$$

where t_o is the maximum time the wave and electron interact $t_c \simeq L/\langle v \rangle$ and $\langle v \rangle$ is the average electron velocity. Equation (27) shows that a tail is established with a velocity equivalent to $(4D_{\parallel} t_c)^{\frac{1}{2}}$ and the temperature of this tail is found to be

$$kT_{TAIL} \simeq 2m_e D_{\parallel} t_c \tag{28}$$

The ratio of the electron tail temperature to the thermal temperature is now given by

$$kT_{TAIL}/kT_e \simeq 4\pi \frac{W_{LH}}{n_o kT_e} \frac{k_{\parallel}}{k_c} \omega_{pe} t_c \tag{29}$$

An important parameter is the length needed to accelerate a particle from v_1 to v_2 this was shown to be given by (Bingham et al 1984)

$$L_{acc} = \frac{\omega_{LH}}{4\pi \omega_{pi}^2} \frac{n_e kT_e}{W_{LH}} \frac{(\Delta v)^2}{v_{Te}^2} \frac{k_c}{k_{\parallel}} \langle v \rangle \tag{30}$$

where $\Delta v = v_2 - v_1$. Using results obtained from Ogo by Scarf et al (1973, 1975) who found that the wave spectrum peaked near the lower hybrid frequency with a normalized energy density of 10^{-3} - 10^{-4} corresponding to electric field strengths between 0.2 - 0.5 Vm^{-1}, we find that the distance L_{acc} required to accelerate electrons from v to 2v, where $v = 2 \times 10^{-7} ms^{-1}$ is $L_{acc} \simeq 2 \times 10^6$ m for a wave energy density of 10^{-3}.

One of the drawbacks of the analytic quasi-linear diffusion theory is that it only involves resonant accelration through Landau resonance and no other mechanism. However, as shown by numerical simultations (Tanaka and Papdopolous 1981) nonlinear effects play an important role in tail formation. One non-linear effect is produced by the trapped ions which have been shown to lead to a positive frequency shift which increases the parallel phase velocity of the waves which makes the waves much more efficient at accelerating electrons than by Landau damping alone. The waves due to the nonlinear effects have characteristics such as the phase velocity increase which are found in an autoresonant accelerator.

The simulations by Tanaka and Papadopoulos (1983) of the modified two stream instability show that 60% of an initial ion-stream energy is transferred via lower-hybrid waves to electrons producing a high energy tail extending out to $7v_{Te}$. Similar particle in cell simulations carried out by Dawson (1985) on the process of electron acceleration by waves around the lower hybrid frequency are shown in Fig 4 plotted together with experimental results obtained from rocket measurements (Bryant et al 1983). Again there is excellent agreement between experiment and simultations.

Sometimes the experimentally observed electron distributions have regions where $\partial f_e / \partial v_{\parallel} > 0$ ie regions with a positive slope such as depicted in figure 5. This feature again cannot be explained by the quasi linear theory presented above. However, the quasi-linear diffusion theory does predict a large velocity anisotropy ie $T_{TAIL} > T_e$. A numerical study by Papdopoulos et al (1977) has demonstrated how an initially flat tail distribution will evolve towards a bump-in-the-tail distribution by the anomalous Doppler resonance instability (Kadomisev and Pogutse (1968)). Physically we can understand this instability as follows: Let us assume that the flat tail distribution has already been established with $T_{TAIL} > T_e$ the streaming electrons in the tail generate waves under anomalous Doppler effect conditions such that

$$\omega = k_{\parallel} v_{\parallel} - \omega_{ce} \tag{31}$$

with negligible Landau-damping

$$\omega / k_{\parallel} \gg v_{Te} \tag{32}$$

From (31) and (32) only particles with velocities $v_{e\parallel} > v_m = (\omega_{ce}/\omega_{pe}) v_{Te} / k_{\parallel} \lambda_{De}$ can be resonant with the waves, Kadomtsev and Pogtuse (1968) have shown that for $\omega_{ce}/\omega_{pe} > 1$ this interaction leads to pitch angle scattering for particles with $v_{e\parallel} > v_m$ and particles with velocities $v_{e\parallel} < v_m$ will be accelerated faster than particles with $v_m > v_{e\parallel}$ and a pile up of particles will occur near v_m. As a consequence the high energy electron tail will develop a positive slope near $v_{e\parallel} = v_m$. Figure (6) shows an experimentally observed distribution function showing the features expected from the anomalous Doppler resonance such as the bump-in-the-tail and the pitch angle scattered higher energy particles. The particles in the beam should be more field aligned than higher energy particles as demonstrated. Using the experimentally obtained parameters it is found that $v_m = 6 \times 10^7$ m/sec in good agreement with the measured position of the beam.

ENERGY FLUX PROFILE ON AURORAL FIELD LINES

In order to obtain an estimate of the power budget of the process we have investigated in a simplified model how power carried initially by an ion-stream at geocentric radial distance R might become distributed between ions, waves and electrons as the radial distance r decrease. We visualize the process as a continuous evolution of ion, wave and electron power as the ions, waves and electrons flow towards the atmosphere. The wave power observed at any point is then an equilibrium level between production by the ion-stream and loss to the electrons.

We consider the case where the magnetic field at very high latitude is a dipole field varying as r^{-3}. The ions moving towards the earth are assumed to be isotropically distributed. The equation for the power balance as a function distance for the ions is:

$$\frac{dP_i(x)}{dx} = -\left(\frac{3}{(R-x)} + \gamma_i\right)P_i(x) \tag{33}$$

where the first term on the RHS is a loss due to magnetic mirroring and the second is the transfer of power to the waves at rate γ_i. Integrity (33) yields

$$P_i(x) = P_i(0)\left[(R-x)/R\right]^3 \exp(-\gamma_i x) \tag{34}$$

where $P_i(0)$ is the initial power in the ions being carried earthwards.

Similarly the equation describing the wave growth and damping is given by (Hall et al 1975)

$$\frac{dP_w(x)}{dx} = -\gamma_w P_w(x) + \gamma_i P_i(0)\left[(R-x)/R\right]^3 \exp(-\gamma_i x) \tag{35}$$

where γ_w is the rate of damping due to electron Landau resonance. Integrating (35) results in:

$$P_w(x) = P_i(0)\,\gamma_i \Big[(a^3R^3 - 3a^2R^2 + 6aR - 6)\exp(-\gamma_w x)$$

$$- (a^3(R-x)^3 - 3a^2(R-x)^2 + 6a(R-x) - 6)\exp(-\gamma_i x) \qquad (36)$$

where $a = \gamma_i - \gamma_w$

The electrons gain power from the waves and lose earthward-directed power due to the mirror force at a rate which depends on the degree of collimation that results from the acceleration. To evaluate the expected degree and effect of collimation we need to consider how the electron distrubtion function is modified by the acceleration process. We shall assume that the electron distribution function is intially a Maxwellian with maximum velocity space density f_o and characteristic velocity v_o. We will consider that each unit of power added will accelerate some of those electrons which have initial parallel velocity $v_\parallel$ in the range $v_{\parallel A} < v_\parallel < v_{\parallel B}$ in such a way that the distribution function develops a plateau between $v_{\parallel A}$ and $v_{\parallel B}$. The absorbed power carried by electrons to the atmosphere is that carried by accelerated electrons that have pitch angles within the loss cone.

The power carried by electrons with parallel velocities between $v_{\parallel A}$ and $v_{\parallel B}$ is

$$P_{AB} = m\pi \int_{v_\parallel = v_{\parallel A}}^{v_{\parallel B}} v_\parallel \, dv_\parallel \int_{v_\perp = 0}^{\infty} (v_\parallel^2 + v_\perp^2)\, v_\perp\, f_e(v_\parallel, v_\perp)\, dv_\perp \qquad (37)$$

For the original Maxwellian $f(v_\parallel, v_\perp) = f_0 \exp(-(v_\parallel^2 + v_\perp^2)/v_0^2)$ where f_o = $n/(\sqrt{\pi}\, v_0)^3$, n is the density in configuration space and v_o is the characteristic velocity, and it may readily be shown that:

$$P_{AB} = m\pi f_0 v_0^4 \left[(v_{\parallel A}^2 + 2v_0^2) \exp(-v_{\parallel A}^2/v_0^2) \right]/4 \tag{38}$$

The power carried by electrons with $v_{\parallel A} < v_\parallel < v_{\parallel B}$ is

$$P'_{AB} = m\pi f_0 \int_{v_\parallel = v_{\parallel A}}^{v_{\parallel B}} v_\parallel \, dv_\parallel \int_{v_\perp = 0}^{\infty} (v_\parallel^2 + v_\perp^2) v_\perp \exp[-(v_{\parallel A}^2 + v_\perp^2)/v_0^2] \, dv_\perp \tag{39}$$

ie

$$P'_{AB} = m\pi f_0 v_0^2 \left[(v_{\parallel B}^4 - v_{\parallel A}^4) + 2v_0^2 (v_{\parallel B}^2 - v_{\parallel A}^2) \right]/8$$

The power required to produce the distortion is then given directly as $P'_{AB} - P_{AB}$

We now find what fraction of this power is carried by electrons within the atmospheric loss cone of half-angle α(r) can be found by setting the upper limit of $v_\perp$ in equations 37 and 39 as $v_\parallel \tan\alpha$.

Thus

$$(P_{AB})_{LC} = m\pi f_0 \int_{v_\parallel = v_{\parallel A}}^{v_{\parallel B}} v_\parallel \, dv_\parallel \int_{v_\perp = 0}^{v_\parallel \tan\alpha} (v_\parallel^2 + v_\perp^2) v_\perp \exp(-(v_\parallel^2 + v_\perp^2)/v_0^2) \, dv_\perp \tag{40}$$

similarly

$$\left(P'_{AB}\right)_{LC} = m\pi f_0 \int_{V_\parallel = V_A}^{V_B} V_\parallel \, dV_\parallel \int_{V_\perp = 0}^{V_\parallel \tan\alpha} (V_\parallel^2 + V_\perp^2) V_\perp \exp[-(V_{\parallel A}^2 + V_\perp^2)/V_0^2] \, dV_\perp \qquad (41)$$

$$= P'_{AB} - m\pi f_0 v_0^2 \exp(-v_A^2/v_0^2) \frac{v_0^2}{4\tan^2\alpha} \Bigg|_{V_\parallel = V_{\parallel B}}^{V_\parallel = V_{\parallel A}} (V_\parallel^2 \sec^2\alpha + V_0^2)\left(\frac{1 + 2\tan^2\alpha}{\tan^2\alpha}\right)\left(\exp \frac{-V_\parallel^2 \tan^2\alpha}{2}\right) \qquad (42)$$

The fraction of absorbed power which is rained in the electron stream as far as the atmosphere can be found from:

$$\varepsilon(\alpha) = \varepsilon(x) = \frac{\left(P'_{AB}\right)_{LC} - \left(P_{AB}\right)_{LC}}{P'_{AB} - P_{AB}} \qquad (43)$$

We can now examine how power accrues in the loss cone as x progresses from 0 to R-1 ie

$$\frac{d\left(P_e(x)\right)_{LC}}{dx} = \varepsilon(x)\, \gamma_w P_w(x) \qquad (44)$$

The results of the calculations are shown in figure 7, in which the ion, wave, and electron energy fluxes are plotted against radial distance. Two calculations were made for the loss of wave power to electrons. The first is for the case where all electrons having the same velocity parallel to the magnetic field are accelerated in the same way. In this case most of the power is transferred to electrons with pitch angles outside the atmosphere. The second is for the case where all of the wave power is transferred to electrons with pitch angles in the atmospheric loss cone (ie $\varepsilon(x)=1$ in equation (46). Also shown in figure 7 are the ion energy flux ($1 mWm^{-2}$) measured by DeCoster and Frank [1979] at radial distances between 10 and $20R_E$, the wave energy fluxes ($0.01-0.1$ mW m^{-2}) estimated from the measurements of wave strength near the lower hybrid frequency between $1-4R_E$ made by Scarf [1973], Gurnett and Frank [1977], and Mozer et al [1980], and the typical electron and ion energy fluxes we have observed just above discrete aurora. The comparison of the calculated and measured energy fluxes suggest that there is sufficient energy flux in the observed lower hybrid waves to account for the electron energy flux close to the atmosphere, and that the ion energy flux at $>10R_E$ is sufficient to account for the wave generation.

CONCLUSION

We have examined the feasibility of electron acceleration by lower-hybrid waves on auroral field lines and have shown that the streams of accelerated electrons (inverted-V's) that are associated with discrete aurora could be produced as a result of a continuous evolutionary process along an auroral flux tube. The generation of the lower-hybrid waves has been considered to be due to instabilities driven by the streaming ions produced in the tail of the magnetosphere by magnetic reconnection processes. The power in the ion-streams and waves associated with the boundary plasma sheet is found to be sufficient to account for the power observed in the electron streams that make up the inverted-V's.

Two linear instability mechanisms have been studied namely the modified two stream instability and the ion loss-cone instability. The energy transfer process takes place in a suitably short distance with an e-folding length along the field lines of about 400 km. The analytic theory for energy transfer to electrons from the waves is based on the quasi-linear wave-particle diffusion model which has demonstrated the effectiveness of the waves in producing a high energy tail, with the observed wave energy density sufficient to accelerate electrons over a distance of the order of $1R_E$. Simulations, however, have shown that nonlinear processes such as particle trapping can enhance the efficiency of tail formation.

Figure Captions

Fig.1 Lower-hybrid wave characteristics.

Fig.2 Spectrum of waves in the magnetosphere at about 4Re from Gurnett and Frank (1977).

Fig.3 Growth rate of lower-hybrid waves due to the modified two stream instability on auroral field lines.

Fig.4 Auroral electron distribution,dots represent experimental values, solid line represents results from a simulation code. J.M.Dawson,private communication.

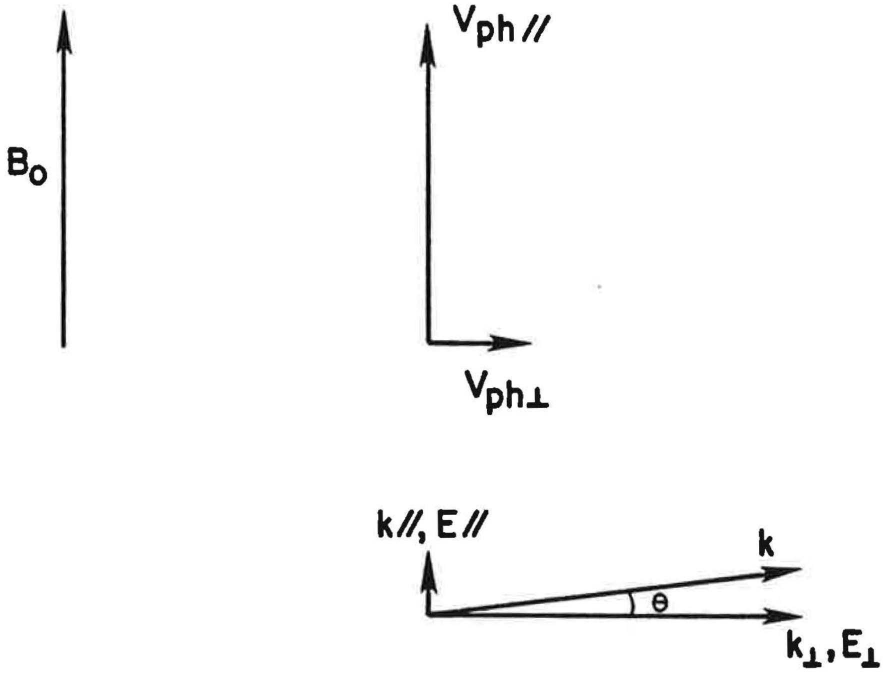
Fig.5 Auroral electron distributions measured at different locations within an arc. Bryant (1983).

Fig.6 Pitch angle dependence of auroral electron distribution function showing a positive slope for electrons with small pitch angles. Bryant (1983).

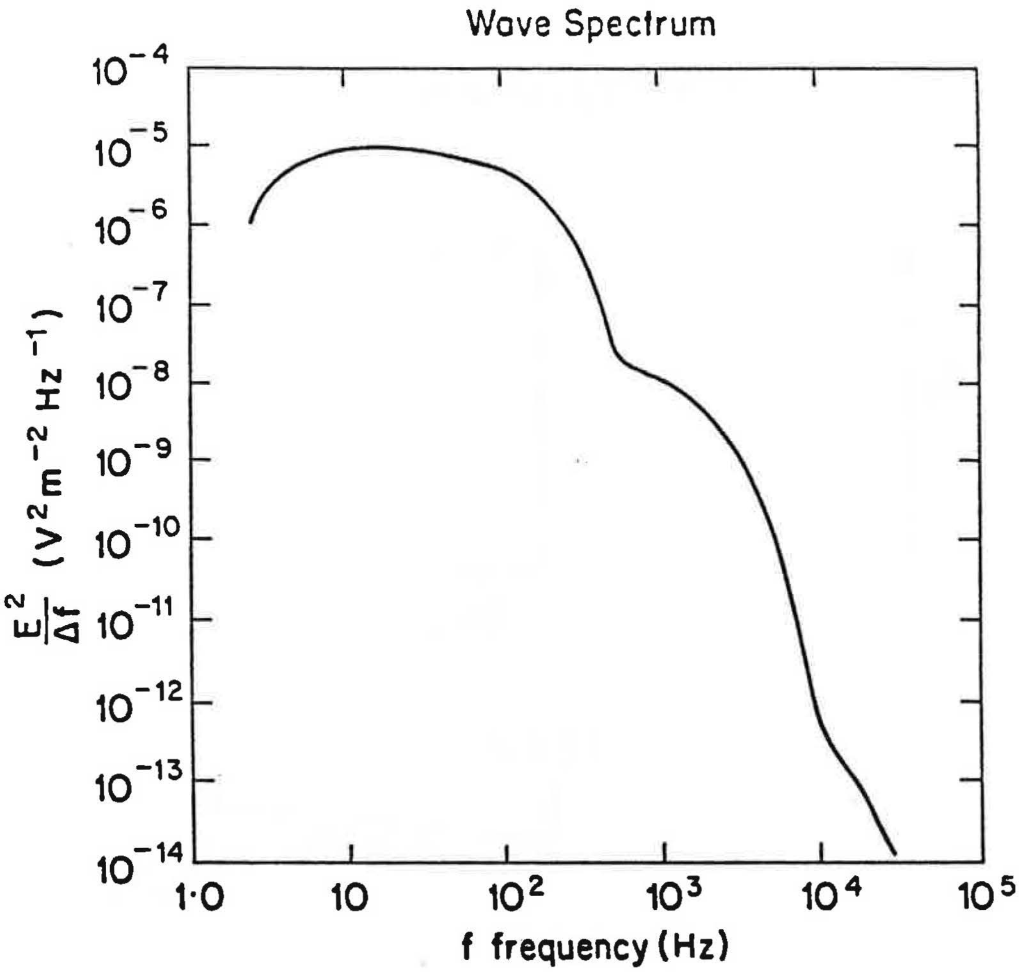
Fig.7 Development of the energy flux profile for ions, waves and electrons on auroral field lines. Curve (a) is calculated assuming that all the power transferred to electrons is transferred within the atmospheric loss cone. Curve (b) assumes that most of the power is transferred outside the loss cone.

Fig 1

Lower hybrid waves



$\theta \neq 0$



Wave Spectrum
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\frac{E^2}{\Delta f}$ $(V^2 m^{-2} Hz^{-1})$
1·0
10
10^2
10^3
10^4
10^5
f frequency (Hz)

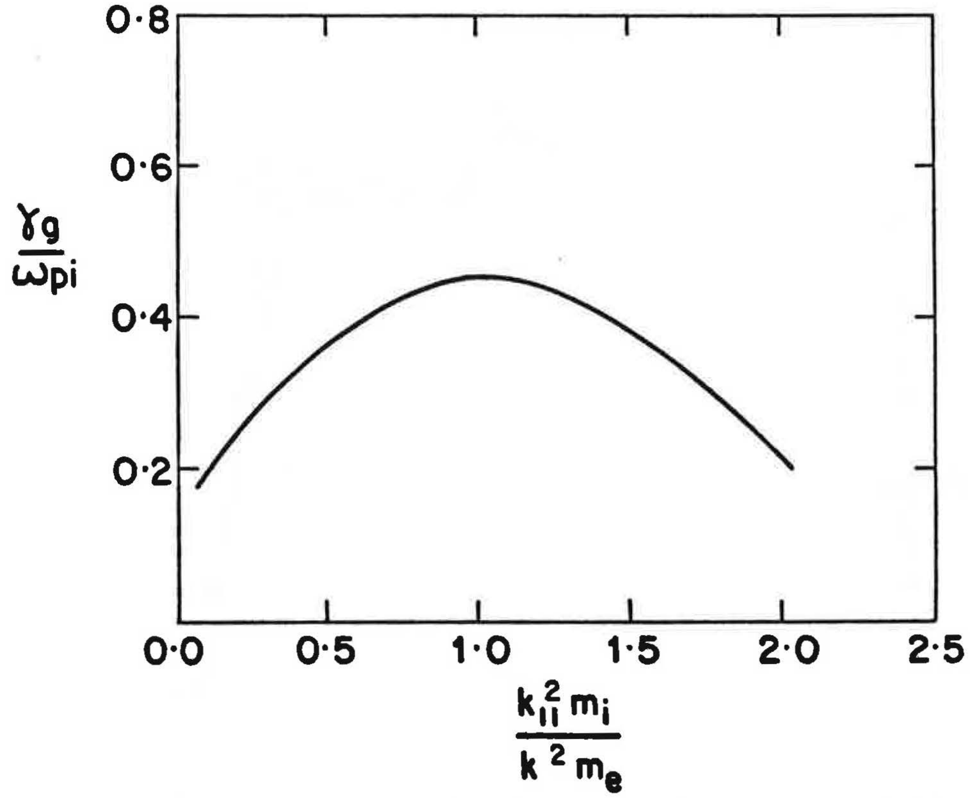
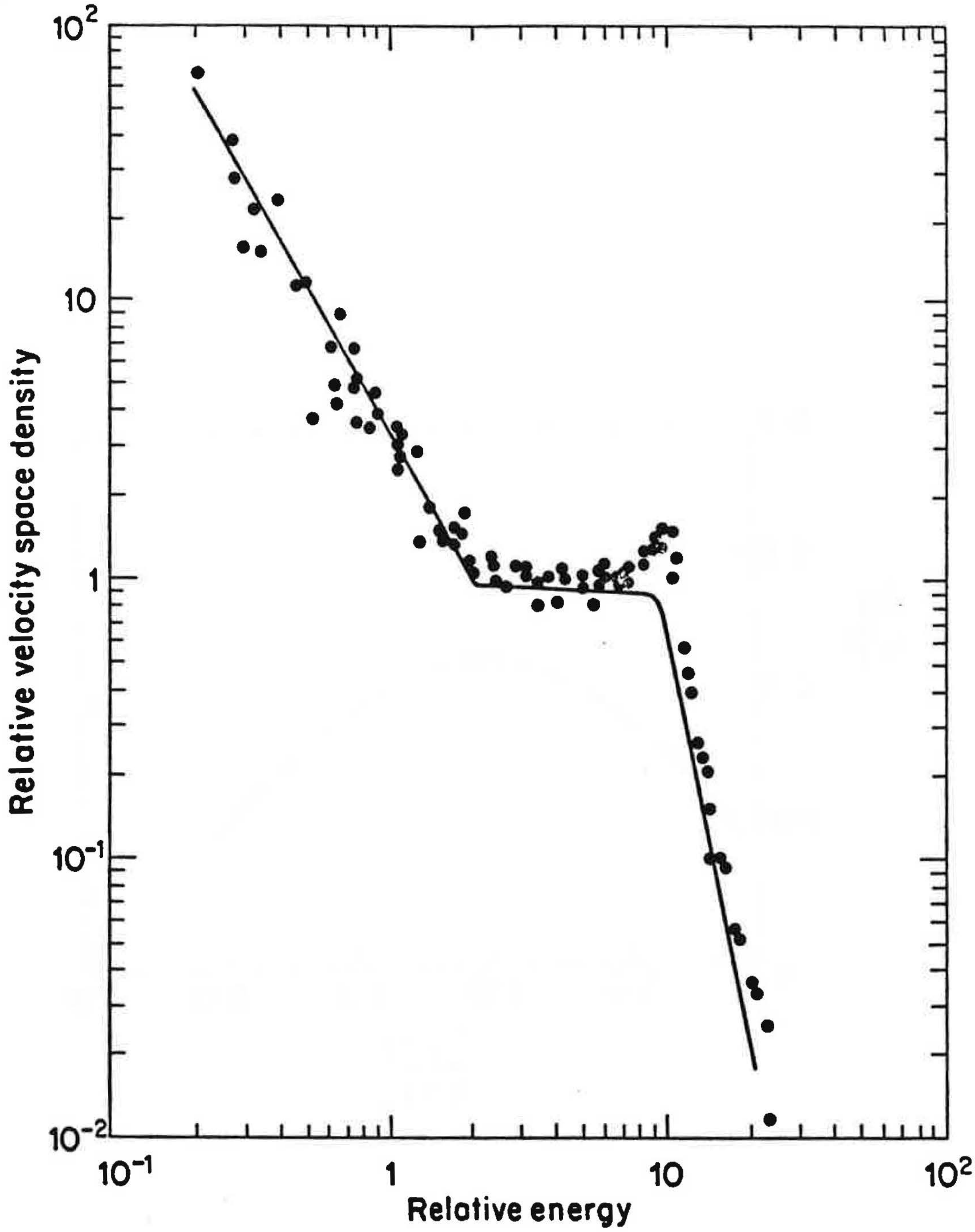
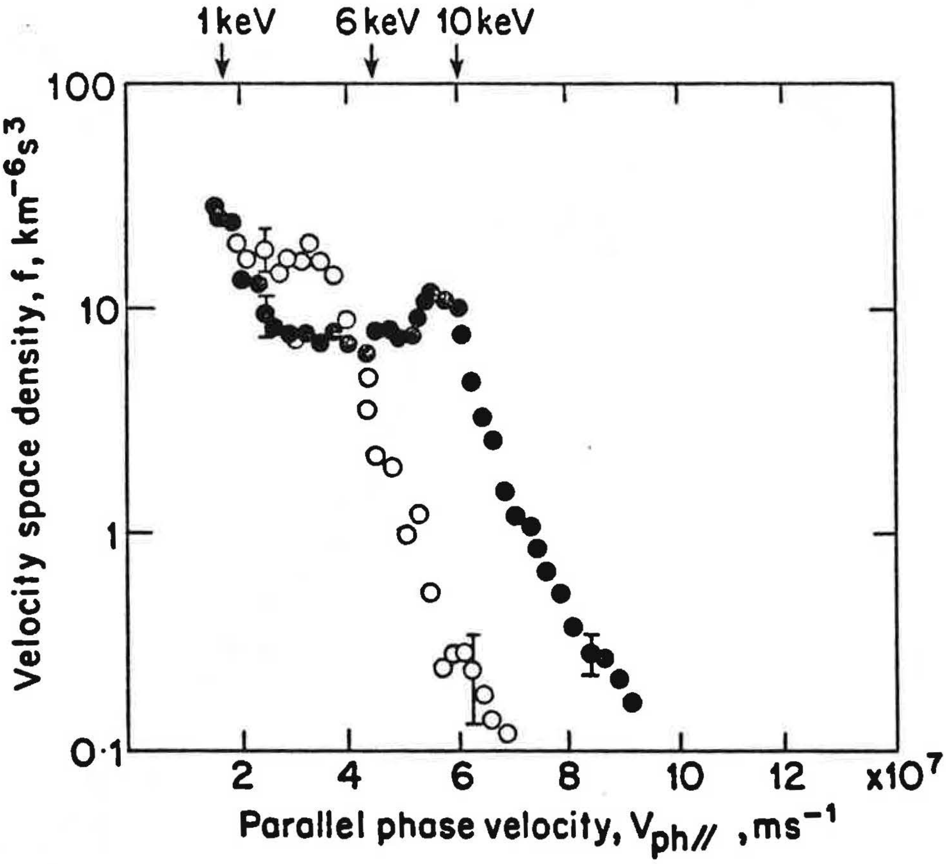

0·8
0·6
0·4
0·2
$\frac{\gamma_g}{\omega_{pi}}$
0·0
0·5
1·0
1·5
2·0
2·5
$\frac{k_{\parallel}^2 m_i}{k^2 m_e}$

Fig 4

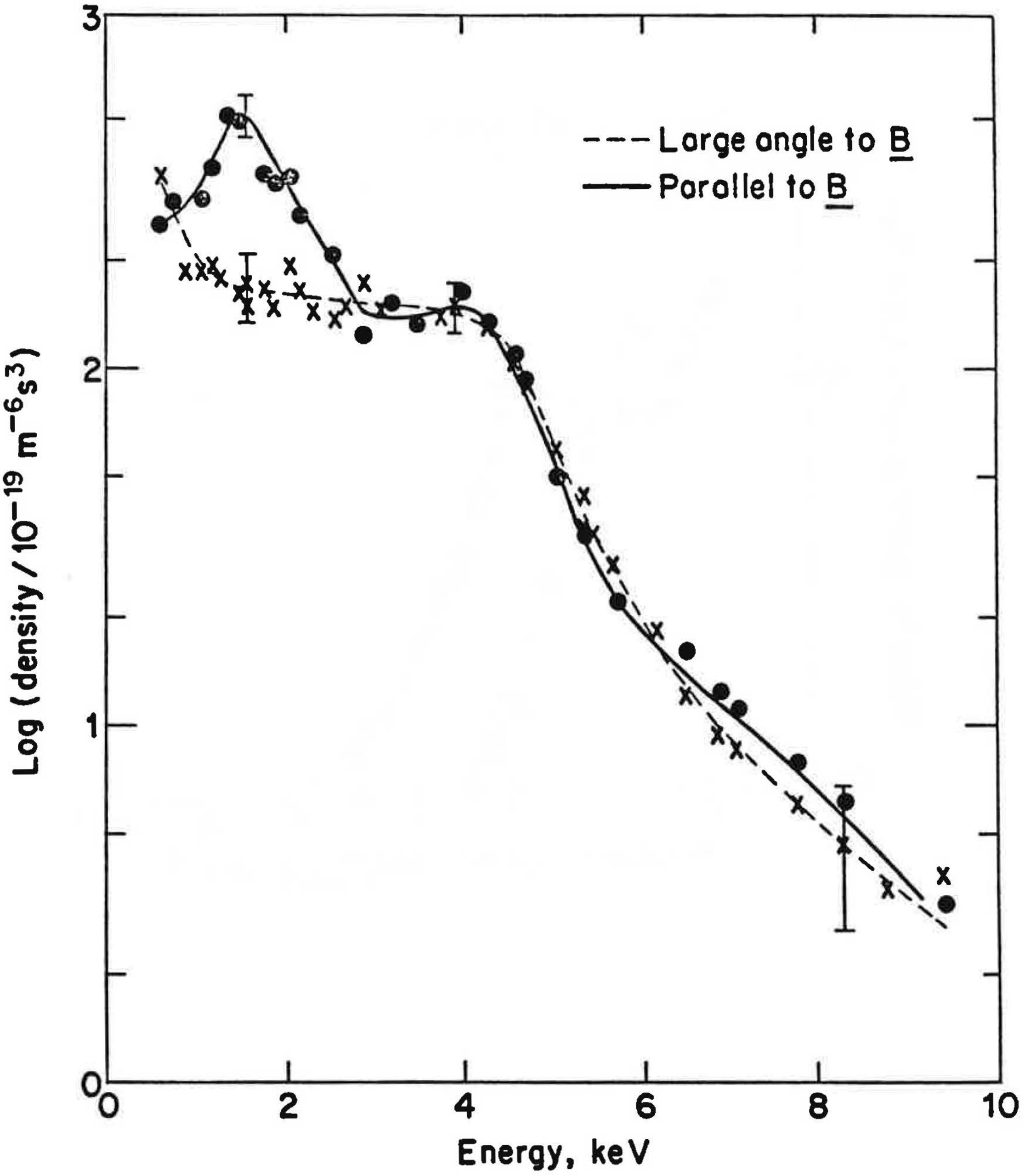


10^2
10
1
10^{-1}
10^{-2}
Relative velocity space density
10^{-1}
1
10
10^2
Relative energy



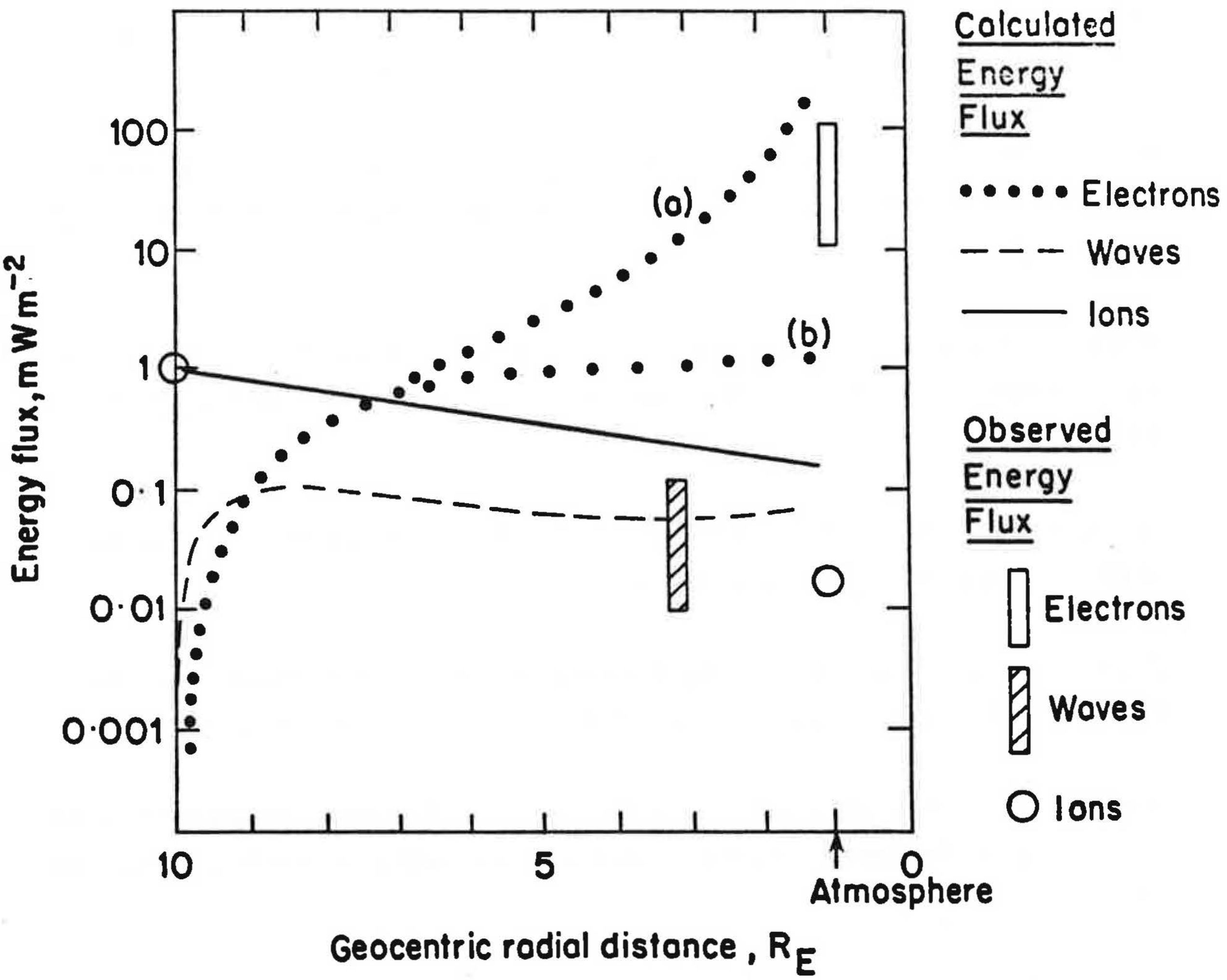
1 keV
6 keV
10 keV
100
10
1
0·1
2
4
6
8
10
12
x10^7
Velocity space density, f, km^-6 s^3
Parallel phase velocity, V_ph// , ms^-1

Fig 6



Large angle to B
Parallel to B
Log (density / 10^{-19} $m^{-6}s^3$)
Energy, keV
0
1
2
3
0
2
4
6
8
10

Fig 7



Energy flux, m W m^{-2}
100
10
1
0·1
0·01
0·001
(a)
(b)
10
5
0
Atmosphere
Geocentric radial distance , R_E
Calculated Energy Flux
Electrons
Waves
Ions
Observed Energy Flux
Electrons
Waves
Ions

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