Destabilization of EIC waves and heating of HPT ions

C S Jayasree & G Renuka
Department of Physics, University of Kerala, Kariavattom, Trivandrum 695 581

and

C Venugopal
Department of Physics, University of Asmara, South Africa

Received 30 April 2002; revised 9 August 2002; accepted 31 October 2002

The electrostatic ion cyclotron (EIC) instability of hot plasma torus (HPT) particles in the auroral region due to field aligned current (FAC) has been studied. The value of FAC density \( J_f \) is estimated from the high time resolution magnetic field data of DE-1 spacecraft at altitudes ranging from 600 km to 2500 km during the magnetic storm of 21 Mar. 1990 during 0001-2000 hrs UT. The FAC destabilizes the EIC wave and the resultant electrostatic turbulence creates an anomalous resistivity. The current driven resistivity produces parallel electric field and high power dissipation. The growth rate of EIC wave decreases as the electron to ion temperature ratio \( T_e/T_i \) increases for weak current density. The anomalous resistivity \( \eta \), parallel electric field \( E_{\parallel} \), power dissipation \( P \) and ion heating rate have been computed. It is found that these parameters decrease as \( T_e/T_i \) increases. When the instability is almost shut off, the ion heating and transversely accelerated ions (TAI) are sharply reduced.

1 Introduction

Plasma wave measurements from the various satellites like Hawkeye 1, Imp-6, DE-1 and DE-2, Viking, etc. show that a broad region of intense plasma wave turbulence occurs in the region of field aligned current (FAC) on high latitude auroral field lines at altitudes above a few thousand kilometres during the periods of substorm activity. The existence of FACs in association with aurora was originally proposed by Birkeland and their importance became evident from the measurements of magnetic field perturbation in the auroral regions by rockets and satellites. From the TRIAD measurements, Zmuda and Armstrong reported that FACs occur over a wide region associated within the whole auroral oval. Iijima and Potemra, after detailed study of FAC, separated them into the region-1 and region-2 current systems. Yamamoto et al. proposed that the region-1/region-2 FACs can be generated as a result of natural distortion of the hot plasma torus (HPT) due to the solar wind convection.

When the plasma electrons drift with respect to ions with an average speed larger than the ion acoustic speed, both the electrostatic and electromagnetic fields grow at the expense of the electron kinetic energy and, as a result, various instabilities set in. The magnetometer data indicate that these waves are spatially correlated with perturbations which are indicative of FACs directed into and out of the auroral ionosphere. Scarf et al. reported the observation of electrostatic plasma wave turbulence associated with FACs in the auroral region. Electrostatic ion cyclotron (EIC) and ion acoustic modes should be unstable in the FAC region associated with the electron precipitation reported by Kindel and Kennel. They compared the two instabilities for a wide range of electron to ion temperature ratio \( (T_e/T_i) \) and suggested that the EIC wave is unstable at smaller current.

Fredricks et al. discussed Ogo-5 observation of FACs, current driven plasma instabilities and possible anomalous resistivity during active periods. A large number of instabilities like Buneman, ion acoustic, ion cyclotron, etc., are driven by FACs. Swift considered the possibility that an ion acoustic instability might produce large anomalous resistivity and parallel electric field. Palmadesso et al. performed a model calculation of the ion heating rate due to EIC turbulence in the topside ionosphere in the absence of plateau formation. The intense FACs destabilize the ion acoustic wave and the resultant electrostatic turbulence creates an anomalous resistivity. This paper reports the results of first attempt in computing the ion heating rate of HPT particles and growth rate of ion cyclotron waves in the...
auroral field lines. The HPT is defined as the co-existing hot plasma particle populations with average energy of 1-10 keV, spread over several degrees of latitude in width in the magnetosphere.

Ashour-Abdalla and Thornell\textsuperscript{11} suggested that EIC waves are excited by FACs and that the instability analyzed by Kindel and Kennel\textsuperscript{6} may be responsible for diffusion of protons into the loss cone. Electrostatic instability produces diffusion both in energy and in pitch angle. The pitch angle scattering of HPT particles with electrostatic waves produces diffuse aurora and the polarization of these HPT particles generate FACs (Ref. 12). The theoretical and experimental observation of ion heating due to EIC waves in the auroral zone was presented by Dakin \textit{et al.}\textsuperscript{13} The original analysis of the linear dispersion relation was made by Drummond and Rosenbluth\textsuperscript{14} and extended by Kindel and Kennel\textsuperscript{6}.

Shalimov and Liperovski\textsuperscript{15} inferred that the turbulence excited on auroral field lines is of EIC and ion acoustic type. The interchange instability of plasma sheet may be responsible for the appearance of auroral arc inside region-2 in which FACs flow out of the ionosphere\textsuperscript{16}. By numerical simulations, Yamamoto \textit{et al.}\textsuperscript{17} demonstrated that the auroral omega band/torch structure is a manifestation of the interchange instability occurring in HPT in the magnetosphere. The behaviour of multi-component anisotropic plasma in a magnetic flux tube, in the presence of current driven EIC turbulence, is studied by Zakharov and Meister\textsuperscript{18}.

It has been shown that the ion cyclotron instability has a lower threshold and, therefore, would be a more likely mechanism for the anomalous resistivity\textsuperscript{19}. As one of the sources of the parallel electric field, the anomalous resistivity of the plasma caused by the broadband electrostatic noise (BEN) is taken into account. The life-time of HPT particles in the auroral region during a geomagnetic storm has been computed\textsuperscript{20}. The occurring anomalous resistivity may cause potential differences of a few kilovolts along the auroral field lines and produce considerable pitch angle and energy diffusion of trapped HPT particles\textsuperscript{21,22}.

In this paper, a study is done on the EIC destabilization by HPT particles under the impact of FAC. By using the high time resolution magnetometer data (MAG-A) from the Dynamic Explorer (DE-1), the value of FAC density is computed. The growth rate of ion cyclotron wave, anomalous resistivity, parallel electric field, power produced per unit volume and ion heating rate in the auroral latitude during a geomagnetic storm, are also estimated.

2 Data and method

2.1 Field aligned currents

To compute the value of FAC density, 6-s average magnetic perturbation data of DE-1 are used. The spacecraft was launched on 3 Aug, 1981 into coplanar polar orbits at altitude ranging from 570 km to 23,000 km for studying interactive processes within the atmosphere-ionosphere-magnetosphere system. The MAG-A high time resolution data set consists of triaxial fluxgate measurements taken every 62.5 ms (i.e., 16 vectors/s). The instrument’s digital resolution ranged from 0.02 nT to 1.5 nT. The gradual commencement of storm of 21 Mar, 1990 during 0001-0000 hrs UT has been considered and it is found that the $B_y$ perturbation is negative or westward throughout the disturbance region of about few thousand kilometres and it lies within $63^\circ \leq A \leq 76^\circ$. The electrons and protons are represented as HPT electrons and protons throughout this paper.

The density and flow direction of FACs are determined from the magnetic disturbance, $B_y$, using

$$J_\parallel = \frac{1}{\mu_0} \frac{\partial B_y}{\partial x} = 8 \times 10^{-4} \frac{\partial B_y}{\partial x} \text{ A/m}^2$$ \hspace{1cm} (1)

where, altitude $x$ is in metres and is directed towards the north, $\mu_0 = 4\pi \times 10^{-7}$ H/m, the permeability of free space, and $B_y$ is the observed disturbance in the east-west direction and is in nanoteslas (nT).

2.2 Electrostatic ion cyclotron instability

The FAC induced instability, competing most with the ion acoustic instability, is the electrostatic ion cyclotron instability. When the electrons and ions have isotropic Maxwellian velocity distributions, with drift velocity $V_d$ parallel to the magnetic field $B_0$, we can use the linear dispersion relation of ion cyclotron waves as

$$\varepsilon(\alpha,k)=1-\sum_{j=0}^{n} \frac{\omega_j^2 \Gamma_j(s_j)}{k^2 V_j^2} \left[ Z(\zeta_j) \cdot \frac{2n\Omega_j}{k||V_j} Z(\zeta_j) \right] = 0$$ \hspace{1cm} (2)

where, $j$ refers to ions or electrons and $Z$ is the plasma dispersion function having argument.
Here, \( I_n\left(s_j\right) \) is the modified Bessel function of order 'n' with the argument.

\[
\omega_p = \left( \frac{4\pi \eta_0 e^2}{m_j} \right)^{\frac{1}{2}}
\]

is the plasma frequency.

\[
V_j = \left( \frac{2T_j}{m_j} \right)^{\frac{1}{2}}
\]

is the thermal velocity.

\[
\Omega_j = \left( \frac{eB_0}{m_j L^3} \right)
\]

is the gyro frequency.

Here, \( n_0 \) is number density of particles and it is taken as \( 10^6/m^3 \), \( e \) the electronic charge, \( T_j \) the temperature in energy units, \( m_j \) the mass of the particle, \( B_0 \) the magnitude of the field at the equator and \( L \) the McIlwain parameter.

Equation (1) allows instability at every ion cyclotron harmonic frequency \( \omega (\omega = \Omega_j) \). Hence, the ion cyclotron wave solution for \( n=1 \) cyclotron harmonic is

\[
\omega = \Omega_j \left( 1 + \frac{T_j}{T_i} \right) \Gamma_1\left(s_j\right) \quad \ldots (5)
\]

The condition for occurrence of electrostatic ion acoustic and electrostatic ion cyclotron instability is \( V_d << V_e \). Ion acoustic instability occurs only in a strongly non-isothermal plasma \( \left( \frac{T_e}{T_i} \gg 1 \right) \). We also assume that for ion cyclotron instability the wave number range is \( k_\perp >> k_\parallel \) and temperature ratio is \( 0.1 < \frac{T_e}{T_i} < 10 \).

When \( \frac{T_e}{T_i} << 1 \), \( \omega = \Omega \), \( \frac{T_e}{T_i} \sim 1 \), \( \omega = 1.2 \Omega \), \( \frac{T_e}{T_i} \gg 1 \), \( \omega = \Omega_i \left( 1 + \frac{T_e}{T_i} \right) \Gamma_1\left(s_{i}\right) \).

The critical drift velocity \( V_c \), and the growth rate of the instability \( \gamma \) are estimated using the relations

\[
V_c = 3V_i \ln \left( 1 + \left( \frac{m_i}{m_e} \right) \frac{1}{V_e} \frac{T_e}{T_i} \right) \quad \ldots (6)
\]

and

\[
\gamma = \pi \left( \frac{T_e}{T_i} \right)^{\frac{1}{2}} \Omega_e \Gamma_1\left(s_i\right) \left[ \frac{V_d}{V_e} - \frac{\omega}{k_\perp V_e} \right] \quad \ldots (7)
\]

where

\[
V_d = \frac{-J_{\parallel}}{en_o}
\]

is the drift velocity of the HPT particles.

\[
k_\parallel = \frac{\Omega_i}{V_i}
\]

\[
k_\perp = 2^{\frac{1}{2}} \frac{\eta}{k_\parallel}
\]

\[
\eta = \frac{V_e}{\omega_{pe} e_0}
\]

where,

2.3 Anomalous resistivity and parallel electric field

The EIC turbulence has been considered as a possible source of anomalous resistivity. When the instability occurs, the field energy grows exponentially. Therefore, the loss of K.E. of electrons is also exponential and the current carried by these electrons is suddenly disrupted. Such instabilities can produce an anomalous resistivity. It has been inferred that the threshold for EIC instability is well within the range of FAC densities. The ion cyclotron anomalous resistivity \( \eta \) is given by

\[
\eta = \frac{V_e}{\omega_{pe} e_0}
\]

where,
\[ \nu_{\text{ic}} = \left( \frac{V_d}{V_a} \right)^2 \left( \frac{T_e}{T_i} \right) \left( \frac{V_i}{I} \right) \]

Here, \( \nu_{\text{ic}} \) is the ion cyclotron collision frequency, \( \varepsilon_0 \) the dielectric constant in free space, and \( l \sim 2R_E \) \( (1R_E=6371 \text{ km}) \) is the scale length or width of the turbulent region. The Ogo-5 and OV3-3 measurements indicate that FAC regions and electrostatic turbulence associated with them can produce anomalous resistivity on high latitude auroral regions on the nightside.

The turbulent resistivity produced by ion cyclotron instability allows parallel electric field to develop along the auroral field line. The parallel electric field for the turbulence is given by

\[ E_\parallel = J_\parallel \eta \]

\[ \ldots (9) \]

2.4 Power dissipation and ion heating rate

The existence of anomalous resistivity leads to an anomalous version of Joule heating effect in plasma in the topside ionosphere or low magnetosphere. The power produced per unit volume is given by

\[ P = \eta J_\parallel^2 \]

\[ \ldots (10) \]

The ETC instability is excited due to FAC in the region where \( V_d > V_{cr} \). When this happens, the transfer of energy occurs from the ion cyclotron waves to ion thermal motion. Hence, the increase of energy occurs in the bulk of the ions that move transverse to the magnetic field. This perpendicular heating of ions would result in their upward energization lessening their chances of precipitation. The process of perpendicular ion energization gives rise to ion distributions which are known as transversely accelerated ions (TAI). The chances of broadband low-frequency waves and ion heating were observed by Viking and Freja Satellites at altitudes up to few thousand kilometres. The anomalous resistivity \( \eta \) associated with ETC instability is related to ion heating rate through the relation

\[ \frac{\delta T_i}{\delta t} = \frac{\Omega_i}{V_d k_\parallel} \left( \frac{T_e}{T_i} \right) \eta J_\parallel^2 \]

\[ \ldots (11) \]

3 Numerical results and discussion

The observed perturbations and altitudes \( (x) \) ranging from 600 to 2500 km obtained from DE-1 in the early and late afternoon sector 1400-2000 hrs MLT at high invariant latitude \( 63^\circ \leq \Lambda \leq 76^\circ \) along the auroral field lines during disturbed conditions \((4^\circ \leq k_p \leq 6^\circ)\) of 21 Mar.1990 are shown in Fig. 1. It is found that magnetic perturbations are negative or westward throughout the disturbance region. Figure 1 shows the variation of magnetic field strength \( B_\parallel \) with altitude \( x \) and this change is due to geomagnetic storm.

Satellite observations of magnetic perturbations transverse to the main geomagnetic field have provided the most direct evidence for the existence of FACs. Figure 2 shows the variation of FAC density \( J_\parallel \) with altitude \( x \). The FAC densities computed from the \( B_\parallel \) variations using Eq. (1) are negative and shows that FAC changes upward in the equatorward part and downward in the polward part. The current density lies between \(-1.5 \times 10^{-7} \text{ A/m}^2\) and \(-6.98 \times 10^{-7} \text{ A/m}^2\) consistent with the findings of Zmuda and Armstrong and Iijima and Potemra. It is also clear that \( J_\parallel \) increases with decreasing altitude as the field strength
The threshold for excitation of ion cyclotron wave is low, but requires drift velocity of electrons greater than ion acoustic velocity. The critical current density required to excite this wave is greater than $-1.45\times10^7$ A/m$^2$. We denote the minimum value of $J_\parallel$ as $J_1 = -1.5\times10^7$ A/m$^2$ and maximum value of $J_\parallel$ as $J_2 = -6.8\times10^7$ A/m$^2$. In the following discussion, these maximum and minimum values of FAC density are used.

Figure 3 represents the variation of $\gamma$ with electron to ion temperature ratio $T_e/T_i$, for the auroral field line at $L=7$, FAC density $J_1$ and $J_2$ and energy $E=2$ and 4 keV. The growth rate is computed by using Eq. (7) for $L=7$ and 8. The result shows that the value of $\gamma$ for $L=8$ is slightly less than that for $L=7$. It is clear from Fig. 3 that the ion cyclotron wave is unstable at the smaller current $J_1$ over the range $0.2<T_e/T_i<4$. This is because the presence of a magnetic field increases the number of plasma modes that can be excited by eliminating the ion Landau damping transverse to the field. This makes possible the excitation of ion cyclotron waves in the case of low electron drift (smaller current). It is found that the EIC instability at $J_2$ is over the range $0.2<T_e/T_i<10$. That is, when the current is increased, the growth rate becomes larger than the ion cyclotron frequency, the periodic gyro motion of the ions is destroyed and the ions become demagnetized. As a result, the ion cyclotron wave is lost at $T_e/T_i = 4$ and the instability changes into ion acoustic type. The $T_e/T_i$ range of ion cyclotron dominance increases with increasing ion mass.

The critical relative drift velocity as a function of $T_e/T_i$ for the ion cyclotron wave obtained from the numerical solution of Eq. (6) is shown in Fig. 4. Here the drift velocity has been normalized to the electron thermal velocity. For low $T_e/T_i$, the threshold of $V_d$ has high values, and is just the ion cyclotron speed due to weak ion cyclotron damping. When the current density is weak and $T_e/T_i$, the ion cyclotron instability is excited. When the current density is large, the instability changes into ion acoustic type due to weak ion Landau damping. When it is further increased, so that $V_d > V_c$, the Buneman instability is excited.

The variation of the anomalous resistivity $\eta$ with $T_e/T_i$ for $J_1$ and $J_2$ and energy $E=2$ and 4 keV can be seen in Fig. 5. Using Eq. (8), $\eta$ can be estimated. At $T_e/T_i = 0.2$, when $E=2$ keV, $\eta = 6.43\times10^3$ $\Omega$-m and when $E=4$ keV, $\eta = 1.818\times10^4$ $\Omega$-m for $J_1$. But when the current increases to $J_2$, $\eta$ decreases to $3.13\times10^2$ $\Omega$-m and $8.87\times10^2$ $\Omega$-m for $E=2$ keV and 4 keV, respectively. For both $J_1$ and $J_2$, $\eta$ decreases to a very small value as $T_e/T_i$ increases. The $\eta$ value on auroral field line is a factor of $10^2$ to $2\times10^2$ greater than Spitzer value. From the computational result, $\eta$ is the same for $L=7, 8, 9$. It is shown from Fig. 5 that $\eta$ is small for large current density and high for small current density. The reason is that ion cyclotron wave is unstable at weak current density for low $T_e/T_i$ and this causes an anomalously large resistivity.

Figure 6 indicates the variation of parallel electric field $E_\parallel$ with $T_e/T_i$ for $J_1$ and $J_2$ and $E=2$ and 4 keV.

The value of $E_\parallel$ computed using Eq. (9) shows that it depends on $\eta$ and $J_\parallel$. For both $J_1$ and $J_2$, $E_\parallel$ decreases.

**Fig. 3**—Curves showing the growth rate $\gamma$ as a function of $T_e/T_i$ for different FAC densities $J_1$ and $J_2$ and energy $E = 2, 4$ keV.

**Fig. 4**—Plot of critical relative drift velocity as a function of $T_e/T_i$. 

as $T_s/T_i$ increases. At $T_s/T_i=0.2$, when $E=4$ keV, $E_{||}=-2.73$ mV/m and when $E=2$ keV, $E_{||}=-0.989$ mV/m for $J_1$. But for $J_2$, $E_{||}$ decreases and becomes $-0.22$ mV/m and $-0.62$ mV/m for $E=2$ keV and $4$ keV, respectively. This is because when the ion cyclotron instability ceases, ion acoustic instability takes over for high $T_s/T_i$.

Figure 7 indicates the variation of power, $P$, produced per unit volume with $T_s/T_i$ for $J_1$ and $J_2$ and $E=2$ and $4$ keV. The value of $P$ is estimated by using Eq. (10). It is found that anomalously high values of $\eta$ means anomalously high power dissipation. Power dissipation is approximately the same for both $J_1$ and $J_2$ and for energy of the HPT electrons at low $T_s/T_i$ and hence the curves coincide. For $J_1$ and $J_2$ at $T_s/T_i=0.2$, and $E=4$ keV, $P=4.33\times10^{-10}$ W/m$^3$ and when the energy decreases to $2$ keV, $P=1.53\times10^{-10}$ W/m$^3$. From Fig. 7, it is seen that as $T_s/T_i$ increases, power decreases. Mozer has found that a current density of $3\times10^{-5}$ A/m$^2$ produced an $E_{||}$ of $10$ mV/m and dissipated a power of $3\times10^{-2}$ W/m$^3$. So, this high power dissipation at low $T_s/T_i$ leads to ion plasma heating in the topside ionosphere or low magnetosphere.

A plot of $\Gamma_1(s_i)$ against $s_i$ is shown in Fig. 8. The value of $\Gamma_1(s_i)$ is computed by using Eqs (4) and (3). It is clear from Fig. 8 that as the normalized perpendicular wave number increases, $\Gamma_1(s_i)$ decreases. For low $s_i$, $\Gamma_1$ increases to a maximum value and then decreases rapidly up to $s_i=20$. When $s_i>20$, there is a slow variation of $\Gamma_1$. From this we can infer that as $k_\parallel$ increases (for ion acoustic wave $k_\perp>k_\parallel$) the function $\Gamma_1$ decreases.

In Fig. 9 we plot the variation of ion heating rate with $T_s/T_i$ for $J_1$ and $J_2$ at $E = 2$ and $4$ keV. Using Eq. (11), ion heating rate can be estimated.

Fig. 5—Variation of anomalous resistivity $\eta$ with $T_s/T_i$ for different FAC densities $J_1$ and $J_2$ and energy $E=2$, 4 keV

Fig. 6—Curves showing the parallel electric field $E_{||}$ as a function of $T_s/T_i$ for different FAC densities $J_1$ and $J_2$ and energy $E=2$, 4 keV

Fig. 7—Plots of power dissipation per unit volume $P$ against $T_s/T_i$ for different FAC densities $J_1$ and $J_2$ and energy $E=2$, 4 keV

Fig. 8—Curves showing $\Gamma_1$ as a function of normalized perpendicular wave number

Fig. 9—Variation of ion heating rate with $T_s/T_i$ for $J_1$ and $J_2$ at $E=2$ and 4 keV.
Fig. 9. Variation of ion heating rate with $T_i/T_e$ for different FAC densities $J_1$ and $J_2$ and energy $E = 2.4$ keV.

Fig. 9 it is found that at $T_i/T_e=0.4$ and $E=2$ keV, ion heating rate is equal to $(12.2 T_i/v_{ion/\sec}$ and $(2.86 T_e) \text{ion/\sec}$ for $J_1$ and $J_2$, respectively. Ion heating rate decreases as the current density and $T_i/T_e$ ratio increase. The EIC instability may be excited for very weak current density and $T_i$/$T_e$. As the current density is increased, growth rate becomes larger than the ion cyclotron frequency. Then the periodic gyro motion of the ions is destroyed and the ions become demagnetized. When this happens, the EIC wave is lost and the instability changes its nature to the ion acoustic type. Palmadesso et al.\textsuperscript{9} have proposed an ion heating rate in the topside ionosphere (1000-10,000 km) in the range (10 $T_i$, -150 $T_e$)/ion/\sec. The EIC instability converts the kinetic energy of electron current into turbulent fluctuation energy, most of which resides with the HPT ions and which ultimately heats the HPT ions. This heating effect is self-limiting, because increasing ion temperature ($T_i$) with respect to electron temperature ($T_e$) tends to stabilize the plasma against further growth of EIC waves. It is evident from the present analysis that ion heating rate rises rapidly until $V_{cr}/V_g$ whereupon the instability is almost shut off. Thus, the ion heating rate and ion acceleration are sharply reduced. These ion heating events occur at various local times and similar ion energization in a sharply confined spatial region poleward of a nightside auroral arc has been observed by the AMICIST sounding rocket\textsuperscript{28} at 900 km, near 2300 hrs MLT.

4 Conclusions
The existence of enhanced low frequency electrostatic turbulence due to EIC instability produced by FAC in the auroral zone and its significant increase with decrease in ion heating rate due to $T_i/T_e$ decrease have been thoroughly examined. The ion heating rate and hence TAI get reduced when the instability is almost shut off ($\gamma \rightarrow 0$). Ion heating by means of EIC wave is suitable for application to plasma in stellarator and magnetic mirror system. The precise knowledge of this ion heating rate and instability shut-off is of utmost importance in the design and operation of thermo-nuclear reactors.

Acknowledgements
The financial support extended by the University Grants Commission, Govt. of India, to one of the authors (CSJ) in the form of Teacher Fellowship is gratefully acknowledged. The authors are indebted to anonymous referees for their valuable suggestions.

References
7 Fredricks R W, Scarf F L & Russel C T, J Geophys Res (USA), 78 (1973) 2133.
8 Swift D W, J Geophys Res (USA), 70 (1965) 3061.
14 Drummond W E & Rosenbluth M N, Phys Fluids (USA), 5 (1962) 1507.
19 Jayasree C S, Renuka G & Venugopal C, Electrostatic ion cyclotron instability of HPT particles in the auroral region.


