TOPSIDE IONOSPHERE ION HEATING DUE TO ELECTROSTATIC ION CYCLOTRON TURBULENCE

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Abstract. We have performed a model calculation of the ion heating rate due to electrostatic ion cyclotron turbulence in the topside ionosphere, with the assumption that the formation of a plateau on the electron velocity distribution is inhibited. Ion temperature profiles are obtained and the implications of the heating effect on anomalous resistivity calculations are discussed.

I. Introduction

There has been considerable interest in recent years in the subject of anomalous resistivity in the topside ionosphere and magnetosphere. High altitude magnetic field aligned potential drops, too large to be sustained by ordinary collisional resistivity, have been postulated to explain some of the more puzzling features of the energy spectra of auroral electron fluxes [Hoffman and Evans, 1968; Whalen and McDiarmid, 1972; Bosqued et al., 1974; O'Brien and Reasoner, 1971, and Paschmann et al., 1972.] There is also evidence that anomalously large field aligned potential drops play a role in the polarization of stable auroral arcs [Fedder, 1974] and of the auroral electrojet [Coroniti and Kennel, 1972].

Kindel and Kennel [1971] have made a parametric study of the linear stability thresholds of a number of current driven instabilities in the environment of the topside ionosphere. The electrostatic ion cyclotron (EIC) instability, which has the lowest threshold of all those considered by Kindel and Kennel, was shown to be unstable to field aligned cold electron fluxes of the order of 10^9-10^{10}el/cm^2/sec. Since fluxes of this order are observed in the auroral zone, EIC turbulence has been considered as a possible source of anomalous resistivity. Hard estimates of the magnitude of the resistivities and potential drops which can be generated by this mechanism do not yet exist in the literature.

In order to calculate these magnitudes one must treat in a self consistent way the effects that the turbulence would have on the ambient ionospheric plasma. In simple models of EIC turbulence in a one dimensional infinite homogeneous plasma, the system is nearly stabilized by the formation of a plateau on the electron distribution function, and the steady state anomalous resistivity is small. Petviashvili [1963] finds that the effective collision frequency in this case is

$$\nu_{eff} \approx \nu_{ei} \, (1 + V_{De}/V_e)$$

where ν_{ei} is the classical electron ion collision frequency, V_{De} is the relative drift velocity of electrons with respect to ions, and V_e is the electron thermal velocity.

Collisions and spatial effects prevent complete flattening of the electron distribution function [e.g., Vedenov, 1968]. One can show that at the turbulence levels predicted by quasilinear theory, and with values of ν_{ei} appropriate to a few thousand kilometers altitude, residual growth lengths for EIC waves after plateau formation are of the order of tens of kilometers. Thus plateau formation does not imply cessation of wave growth in the ionosphere, and one expects the instability to be saturated at higher levels by some other mechanism. EIC turbulence levels in excess of the quasilinear values have also been observed in Q machines [Benford et al., 1973; Buchel'nikova and Salimov, 1969]. It is also possible that other processes operative in the complex environment of the real ionosphere and magnetosphere further inhibit plateau formation. For example processes which mix the parallel and perpendicular electron velocities (pitch angle scattering) tend to isotropize the electrons in velocity space and would thus destroy a plateau. As yet there exists no observational data from which we might infer the actual shape of the electron distribution function for cold ambient electrons in the topside ionosphere, and the question of whether or not a plateau forms is the subject of theoretical debate.

We shall not attempt to settle this question. Instead, it is the purpose of this letter to consider the limiting case in which plateau formation is completely inhibited. In this case another effect, ion heating, arises to bring the system to near stability. The electrostatic ion cyclotron instability converts the kinetic energy of electron current flow into turbulent fluctuation energy, most of which resides with the ions and which ultimately appears as ion thermal energy. Model calculations such as the one below, in which the ion temperature (T_i) is assumed to be held fixed, suggest that the ion heating rate is very large; the rate at which the turbulence pumps energy into the ions (up to 150 T_i/sec/ion, where T_i is in energy units) is much larger than the rate at which energy can be pumped out by any of the obvious heat transfer or transport processes. The heating effect appears to be self limiting, however, because increasing T_i with respect to the electron temperature (T_e) tends to stabilize the plasma against further growth of EIC waves. In equilibrium the system should be close to a marginally stable state at each altitude, with a residual instability and heating rate determined by the rate at which energy can be transferred out of the turbulent region. We have obtained ion temperature profiles consistent with an equilibrium of this type.

An interesting correlative of the heating effect is the tendency of EIC turbulence to drag out the tail of the ion distribution and produce superthermal ions. This effect might contribute to the energization of the hot O^+ ions observed by Shelley et al. [1972] in the inner magnetosphere.

II. Estimate of the Ion Temperatures

In order to illustrate the way in which turbulent ion heating by EIC waves in an unstable plasma drives the plasma toward marginal stability, it is useful to perform a model calculation of $\delta T_i/\delta t$. The heating rate, which is proportional to the fluctuation energy density, exceeds the rate at which conventional processes cool the ions even for very modest turbulence levels, and so our conclusions are quite insensitive to the details of the saturation mechanism. Possible saturation mechanisms include ion resonance broadening [Dum and Dupree, 1970] and nonlinear ion Landau damping [Petviashvili, 1963], and these predict similar steady state amplitudes for the turbulence. For sake of definiteness, we shall assume that resonance broadening is the operative mechanism.

One can show [e.g., Liewer and Krall, 1973] that the i^{th} particle species of a multicomponent plasma is heated by electrostatic turbulence at a rate given by

$$\left.\frac{\delta T_i}{\delta t}\right|_{turbulence} = -\frac{4}{3n_i}\sum_{\underset{\sim}{k}} \mathrm{Im}\left\{(\omega_k - \underset{\sim}{k}\cdot\underset{\sim}{V}_{Di}) \times \epsilon_i(\underset{\sim}{k},\omega_k)\right\} \frac{|\delta E_k|^2}{8\pi}$$
$$\approx -\frac{4}{3n_i}\overline{\mathrm{Im}\left\{(\omega_k - \underset{\sim}{k}\cdot\underset{\sim}{V}_{Di})\epsilon_i(\underset{\sim}{k},\omega_k)\right\}} \times \sum_{\underset{\sim}{k}} \frac{|\delta E_k|^2}{8\pi} \qquad (1)$$

where T_i, n_i, and $\underset{\sim}{V}_{Di}$ are the temperature, density, and fluid velocity of the i^{th} particle species, ω_k and $\underset{\sim}{k}$ are the complex frequency and (real) wavevector of a Fourier component of the turbulence, $\epsilon_i(\underset{\sim}{k},\omega_k)$ is the contribution of the i^{th} species to the dielectric function, and $|\delta E_k|^2/8\pi$ is the fluctuation energy density of the $\underset{\sim}{k}^{th}$ wave. The bar in equation (1) denotes typical or average values. If we assume that the turbulence saturates by ion resonance broadening, then, for a single singly charged ion species,

$$\sum_k \frac{|\delta E_k|^2}{8\pi} \approx \frac{\overline{k_\perp^2}}{2\pi e^2} T_i^2 \left(\frac{\overline{\omega}_k - \Omega_i}{\Omega_i}\right)^2 \qquad (2)$$

where e is the electronic charge and Ω_i is the ion cyclotron frequency (we have suppressed a factor of order unity in (2)). As shown by Dum and Dupree, we can obtain the appropriate nonlinear dielectric function from the linear one by making the substitution $\omega_k \to \omega_k + i\Delta\omega_k$ for each of the waves in the unstable part of the spectrum. At saturation ω_k is a real frequency and $\Delta\omega_k$ is the linear growth rate of the wave, γ_k^L. In the rest frame of the ions, and in the parameter regime considered by Drummond and Rosenbluth [1962], one obtains the result

$$\mathrm{Im}\ (\omega_k - \underset{\sim}{k}\cdot\underset{\sim}{V}_{Di})\epsilon_i(\underset{\sim}{k},\omega_k + i\Delta\omega) \approx -\frac{.2\gamma_k^L\Omega_i^2}{k^2\lambda_{Di}^2(\omega_k - \Omega_i)^2} \qquad (3)$$

where $\lambda_{Di} = (T_i/4\pi n_i e^2)^{\frac{1}{2}}$ is the ion Debye length. Equations (1) - (3) yield

$$\frac{1}{T_i}\left.\frac{\delta T_i}{\delta t}\right|_{turbulence} \approx \overline{(k_\perp^2/2k^2)}\ \overline{\gamma_k^L} \approx \overline{\gamma_k^L}/2 \qquad (4)$$

Typical linear growth rates for these modes, when well above their instability threshold and when $T_i/T_e \sim 1$, are $\sim .1\Omega_i$. Thus (4) implies heating rates in the topside ionosphere (1000-10,000km) in the range 10-150 T_i/ion/sec., for H^+ ions. This is the rate at which energy would have to be transported out of the turbulent region in order to maintain $T_i \sim T_e$.

These heating rates are extremely large and apparently unsustainable. One can gain some insight into the way the system evolves by noting that the growth rate γ_k^L is a decreasing function of T_i. The instability occurs when V_{De}, assumed parallel to $\underset{\sim}{B}$ in the rest frame of the ions, is greater than a critical velocity V_c, which is an increasing function of T_i [Kindel and Kennel, 1971], hence increasing T_i drives $V_c(T_i) \to V_{De}$ and $\gamma_k^L(T_i)$, $\delta T_i/\delta t|_{turbulence} \to 0$. One can imagine the following sequence of events: a field aligned current is established and the instability is excited in the region where V_{De} is initially greater than V_c. The ion temperature and the critical drift V_c rise rapidly until $V_c \approx V_{De}$ at each altitude, whereupon the instability is almost shut off ($\gamma_k^L \to 0$), and the turbulence and heating rate are sharply reduced. An equilibrium is established in which the residual turbulence pumps heat into the ions at just the rate at which thermal conductivity and other processes can pump it out of the turbulent region.

The linear dispersion relation [see for example Drummond and Rosenbluth, 1962 or Kindel and Kennel, 1971], augmented by the condition $V_c = V_{De}$, can be solved numerically to determine values of the function T_i (altitude) consistent with the marginally stable equilibrium described above. Typical results are shown in Figs. 1 and 2, which were calculated for a hydrogen plasma. Local ion temperatures get substantially higher than the electron temperature before a steady state is achieved. It should be pointed out that Banks (private communication) has recently suggested a collisional mechanism operative at lower altitudes which also leads to elevated ion temperatures.

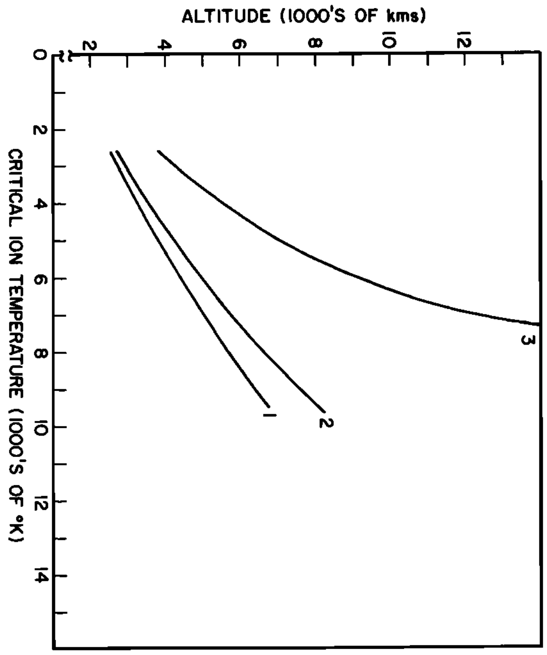

Fig. 1 Critical ion temperatures vs. altitude. Electrostatic ion cyclotron waves are marginally stable when $T_i = T_i$ critical. These curves were calculated with $T_e = 2600°K$ and 1) Flux = 10^9 el/cm^2/sec at 200 km and the "trough" electron density profile of Kindel and Kennel, 2) Flux = 10^{10}el/cm^2/sec, "quiet auroral" n_e profile, and 3) Flux = 10^{11}el/cm^2/sec, "disturbed auroral" n_e profile.

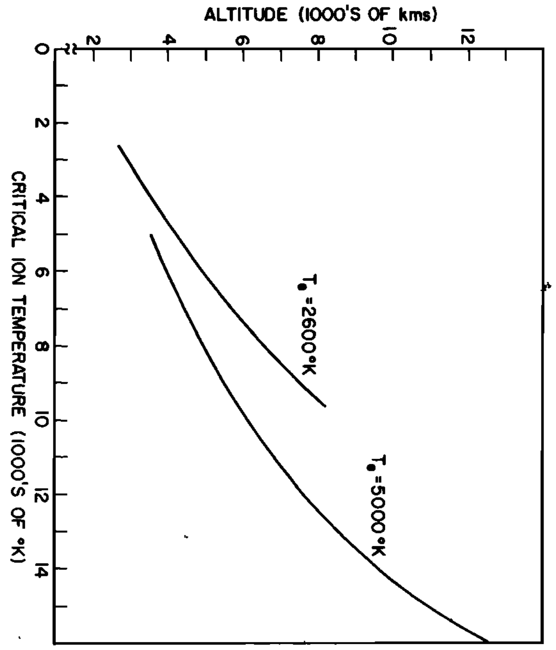

Fig. 2 Variation of T_i critical profiles with T_e. These curves were calculated with an electron flux of 10^{10}el/cm^2/sec at 200 km and the "quiet auroral" electron density profile of Kindel and Kennel.

III. Anomalous Resistivity

The anomalous resistivity η associated with EIC turbulence is related to the heating effect just discussed via the relation

$$\frac{3}{2} n_i \left.\frac{\partial T_i}{\partial t}\right|_{\text{turbulence}} = J_\| E_\| = \eta J_\|^2 \qquad (5)$$

where $J_\|$, $E_\|$ are the parallel current density and electric field and we have neglected the slower electron heating rate. It is clear that the resistivity as well as the ion heating rate must be sharply reduced as T_i approaches $T_{i\ \text{critical}}$. In the steady state

$$\left.\frac{\partial T_i}{\partial t}\right|_{\text{turbulence}} + \left.\frac{\partial T_i}{\partial t}\right|_{\substack{\text{heat}\\ \text{transfer}}} = 0 \qquad (6)$$

where $\partial T_i/\partial t\ |$heat transfer is the effective cooling rate due to heat transfer processes. One can obtain a rough estimate of the anomalous resistivity in the steady state by eliminating $\partial T_i/\partial t\ |_{\text{turbulence}}$ between (5) and (6) and studying the heat transfer processes.

Wave energy can be convected out of the turbulent region at the group velocity, which for EIC waves is $\leq V_i$, the ion thermal velocity. V_i is also an upper limit to the velocity with which conduction processes carry away heat, hence an upper limit on the contributions to $\partial T_i/\partial t\ |$ heat transfer from thermal conduction and wave convection processes is $\sim T_i V_i/L$, where L is the scale length or width of the turbulent region. The contribution of the polar wind flow is also $\sim T_i V_i/L$. If only these processes are operative one can combine $N = \nu_{eff} m/n_e e^2$, $J_\| = n_e e V_{De}$, and $T_e = 1/2\, m_e V_e^2$ with (5) and (6) to obtain

$$\nu_{eff} \leq \left(\frac{V_e}{V_{De}}\right)^2 \left(\frac{T_i}{T_e}\right)\left(\frac{V_i}{L}\right) ,$$

which is valid when V_{De} is well above V_c. At an altitude of 5000 km, curve 2 of Fig. 1 gives $T_i \approx 2.4\, T_e \approx 6100°K$, and $V_i \approx 12$ km/sec. With $V_E/V_{De} = 1.5$ and $L \approx 100$ km, one finds $\nu_{eff} \lesssim .6$/sec., which is roughly ten times the value of ν_{ei} appropriate to these parameters.

IV. Conclusion

Model studies of electrostatic ion cyclotron turbulence in the topside ionosphere suggest that in the absence of plateau formation the instability leads to rapid and substantial ion heating. The anomalous resistivity associated with the turbulence is limited by the heating effect.

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