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ANOMALOUS RESISTIVITY ON AURORAL FIELD LINES

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Abstract. Conditions that exist along auroral field lines ($\delta n_i/n > .25$, $\Omega_e/\omega_e > 1$) act to break the adiabatic invariance of the electron magnetic moment, cause strong anomalous dc resistivity, and generate electron distributions in good agreement with observations.

Introduction

The understanding of acceleration processes in the auroral zones due to parallel electric fields is closely connected with the problem of one-dimensional anomalous resistivity and the breakdown of runaway acceleration. The one-dimensionality comes from the fact that in the auroral regions of interest (i.e., h > 1000 km), $\Omega_e/\omega_e > 1$ (where ω_e, Ω_e are the plasma and cyclotron frequencies). In this case, the Larmor radius of the electrons is less than the Debye length, so that even in the case of ion acoustic turbulence of Debye length scales, the magnetic moment of the electrons ($\mu = mv_\perp^2/2B$) is an adiabatic invariant. The weak magnetic field results for anomalous resistivity are not directly applicable since they result from the elastic scattering of electrons by low frequency fluctuations. The rapid scattering converts the directed velocity into heating and the appearance of anomalous resistivity. For $\Omega_e > \omega_e$, the elastic scattering is not allowed since μ is constant and the electrons can only slow down by parallel diffusion. However, as noted by Petviashvili [1963], the parallel diffusion is accompanied by the formation of a quasilinear plateau, which reduces the anomalous friction and produces trivial resistivity changes, independently of the amplitude of the low frequency waves. A corollary puzzle is what, if anything, inhibits the electrons in the plateau region as well as the negative slope region from freely accelerating [Dupree 1970; Papadopoulos, 1977]. If distributed parallel electric fields are to exist in the auroral regions, the above questions should be answered.

It is the purpose of the present letter to demonstrate that under conditions prevailing in the aurora, the conservation of the first adiabatic invariance is violated for electrons above a certain threshold velocity. This effect combined with trapping of a major portion of the electron distibution function, by large amplitude ion cyclotron waves such as observed by S3-3 [Kintner et al., 1978] and in laboratory experiments [Bohmer and Fornaca, 1979], is sufficient to answer the major questions posed above and reproduce most of the observed features of the auroral energetic electron fluxes.

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Physical Model

Consider a plasma in a uniform magnetic field $\underline{B}_0$ with $\Omega_e > \omega_e$, and an electric field E_0, parallel to B_0, which causes the electrons to acquire a drift velocity v_d such that for a $T_e/T_i \approx 1$ plasma drives an ion cyclotron wave. There are two basic questions to be answered. First, what ultimately limits the growth? Second, what, if anything, inhibits the electrons from freely accelerating?

Several processes have been discussed in the literature for limiting the growth [Dum and Dupree, 1970; Palmadesso et al., 1974]. In view of the recent experimental evidence for large amplitude ($\delta n/n \approx 1/2$) coherent ion cyclotron waves in the aurora [Kintner et al., 1978] we consider here trapping as the basic stabilization mechanism. The effect of large amplitude low frequency density fluctuations on the plasma resistivity has been recently examined by Rowland et al. [1981]. It was shown, that by including the quasineutrality effect, most of the electrons can be trapped for $\delta n/n > 1/4$ independent of the detailed shape or spacing of the cavities. The electron distribution function is composed of a central part carrying little or no current, and a runaway tail of density n_r due to the untrapped electrons, which carry the current. Therefore $J(t) = n_r e v_r(t)$ where the ratio n_r/n is controlled by the level of $\delta n_i/n$, as shown in Rowland et al. [1981]. In the absence of a mechanism that can break the adiabatic invariance of the energetic electrons, $v_r \approx (eE_0/m)t$. From the above we see that the existence of a steady or quasi-steady state reduces to the answer to the second question, i.e., the mechanism that can inhibit the free acceleration of runaways.

To answer this question, we examine the stability of distributions which are composed of a cold core with a runaway tail. The linear stability was studied by Kadomtsev and Pogutse [1967], who showed that low frequency oscillations $\omega_k = \omega_e k_\parallel/k \ll \Omega_e$, where $k_\parallel$ is the wave vector along the magnetic field, are unstable even for flat distributions. These modes are principally driven by the first cyclotron resonance at velocities $(\omega_k + \Omega_e)/k_\parallel$. The instability has a growth rate $\gamma_k \approx n_r/n\,(\omega_e/\Omega_e)^2\omega_k$. The nonlinear theory of the instability has been studied extensively [Papadopoulos et al., 1977; Liu et al., 1977; Haber et al., 1978]. It was shown there that it results in a fast isotropization for particles with velocities $v_\parallel > v_c \approx 3(\Omega_e/\omega_e)v_{te}$ (v_{te} is the electron thermal velocity). A consequence of this is the breakdown of the adiabatic invariance for electrons with $v_\parallel > v_c$. An additional slowing down

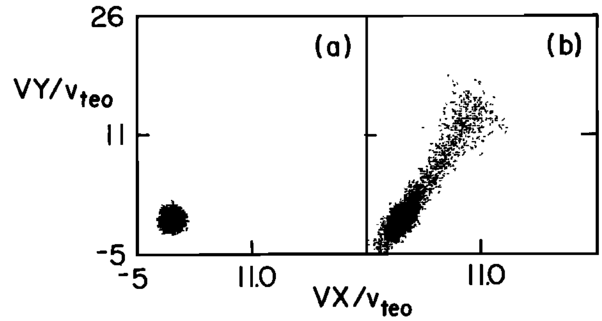

Fig. 1 The initial 1D acceleration of the electrons parallel to the magnetic field B and E_o is at 55° to the axis. (a) initial distribution, (b) distribution at 2000 ω_e^{-1}.

process was discussed first in Papadopoulos et al. [1977] and confirmed by particle simulations by Haber et al. [1978]. Since only particles with $v_\parallel > v_c$ participate in the resonant scattering and have their $v_\parallel$ reduced, electrons will tend to pile up at v_c leading to the formation of a beam. This distribution function can suffer friction in the parallel direction due to wave emission not only by the cyclotron resonance but also by Cerenkov-type beam plasma instability at the lower or upper hybrid branch. Moreover, in the presence of a constant dc electric field this piling up can be enhanced by particles being accelerated up from lower velocities. This reappearance of an electron beam and the slowing down of the electrons in the parallel direction will further isotropize the electron distribution function.

Another interesting effect that is seen in the simulations is the acceleration of particles in the opposite direction to the electric field. The electrostatic waves that are generated in the parallel direction can be backscattered by the ion fluctuations and create superthermal tails by Landau damping. These particles can also interact via the normal Doppler resonance [$v = (\omega_k - \Omega_e)/k_\parallel$] with the waves that are pitch angle scattering the runaways and isotropize the counter streaming particles.

Simulations

We report next the results from a series of particle simulations that combine the effects of finite ion cavities and pitch angle scattering at the anomalous Doppler resonance (ADR). The parameters for the simulations are the same as those used by Haber et al. [1978]. However, instead of starting with a runaway distribution, we start with a Maxwellian distribution and a fixed ion cavity with an effective depth of 0.3. Since the ions will respond on an ion cyclotron timescale, fixed ions are an accurate approximation for these simulations. We will apply a constant dc field to show the formation of the runaway distribution such as was seen in the earlier strictly one-dimensional simulations of Rowland et al. [1981]. We will then continue to drive the electrons to determine the effect of the pitch angle scattering on the further acceleration of the electrons.

Figure 1a shows the initial electron distribution. The magnetic field is at 55° to the x axis and $\Omega_e = 2\omega_e$. The electric field is parallel to B and has a magnitude of $0.01(m/e)v_{teo}\omega_e$. [v_{teo} is initial electron thermal velocity]. Figure 2b shows the electron velocity distribution at 2000 ω_e^{-1}. The ion cavity has prevented the bulk of electrons from being accelerated and one can see the cold dense core of electrons at zero velocity. The untrapped electrons accelerated along the magnetic field forming a flat runaway tail. One can see that the temperature of the electrons transverse to the field did not increase and up to this point the acceleration was 1D parallel to the magnetic field. However, the high velocity edge of the distribution has become greater than v_c and these particles started to pitch angle scatter as seen by the spreading of the upper edge of the distribution.

At this point in time, when 2D effects started taking place, the simulation was stopped. This state was used as an initial state for a series of simulations using different values for the dc electric field. Our earlier theoretical and computational work [Rowland et al., 1981] demonstrated that during the initial 1D stage, changing the strength of the dc electric field did not effect the formation of the runaway distribution beyond changes in the timescale; namely, with a stronger electric field the runaway distribution formed faster. The simulation presented in detail here had an electric field starting from 2000 ω_e^{-1} of magnitude $2\times10^{-3}(m_e/q)\,v_{teo}\,\omega_e$. As the pitch angle scattering continues, the formation of a beam in the parallel direction similar to the one seen by Haber et al. [1978] is observed. The region of positive slope is unstable to Cherenkov interactions with both lower and upper hybrid waves. This acts to reduce the parallel current and to further symmetrize the distribution. Figure 2a shows the distribution at 3800 ω_e^{-1}. No further parallel acceleration of the electrons is observed. Electrons with $v_\parallel > v_c$ which could be pitch angle scattered to large $v_\perp$ were slowed down by the beam instability. Thus one sees electrons with $v_\parallel < v_c$ but with $v_\perp \gg v_{ter}$. This isotropization continues. Figure 2b shows the electron distribution function at 8800 ω_e^{-1}. It is composed of a cold dense core of electrons surrounded by a hot, isotropic cloud.

Figure 3 shows the parallel electron distri-

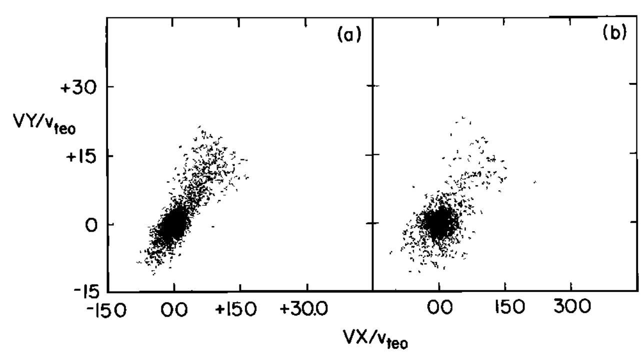

Fig. 2 As the electrons continue to accelerate $v > v_c$, the pitch angle scattering breaks the invariance of μ and strong transverse heating sets in. (a) t = 3800 ω_e^{-1} (b) t = 8800 ω_e^{-1}.

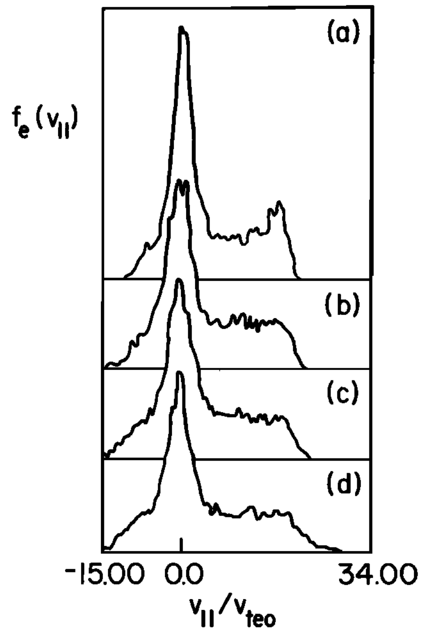

Fig. 3 The parallel electrons distribution. The pitch angle scattering prevents the free streaming acceleration of the electrons. t = 2400, 3200, 4800, 8800 ω_e^{-1} (a,b,c,d).,

bution at 2400, 3200, 4800, 8800 ω_e^{-1} (a,b,c,d). The high velocity beam seen at 2400 ω_e^{-1} is due to the pitch angle scattering. By 3200 ω_e^{-1} beam instabilities have flattened the runaway distribution. It is clearly seen that the instability at the anomalous Doppler resonance prevents electron runaway. If the high velocity electrons had continued to freely accelerate the upper edge of the distribution would have been at the right edge of Fig. 4d.

Figure 5 shows the growth of the parallel drift velocity normalize to the initial electron thermal velocity. Note that the time axis between 0 and 2000 ω_e^{-1} is stretched by a factor of five to compensate for E_o being five times larger during that time. Thus the time axis is linear in terms of the effective acceleration time, $E_o t$. Between 0 and 150 ω_e^{-1} the ion cavity was adiabatically formed in the plasma. At 150 ω_e^{-1} the dc electric field was turned on. The solid line shows for comparison the rate of acceleration of the electrons in the absence of the cavity. At approximately 2000 ω_e^{-1} the

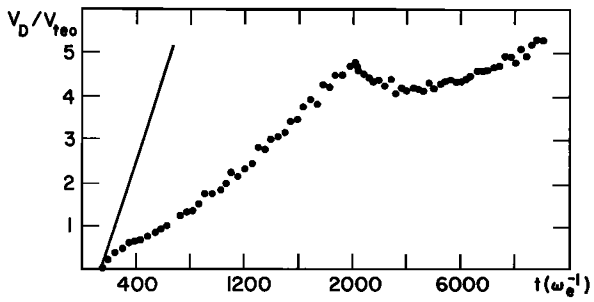

Fig. 4 The average electron drift velocity. When $v > v_c$, the pitch angle scattering clamps the current.

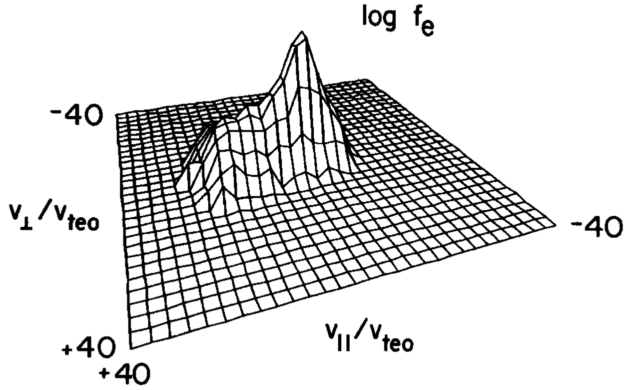

Fig. 5 A 3D plot of the log of the electron distribution seen in Fig. 2b. Note the cold central core and the hot isotropized electrons.

velocity of the fastest particles $> v_c$ and pitch angle scattering begins. The current continues to increase until approximately 2300 ω_e^{-1} when the instability at the ADR has grown to such a level that it removes energy from the parallel motion slowing the electrons down faster than E_o accelerates them. The current is clamped and strong transverse heating is observed. Finally, at much longer times ($>$ 7000 ω_e^{-1}) the current begins to increase again but at a slower rate than during the 1D stage. For $v_{\parallel} > v_c$ the instability heated the plasma so that $\partial f/\partial v_{\parallel} \approx \partial f/\partial v_{\perp}$ (or $T_{\parallel} \approx T_{\perp}$). The electric field can begin to increase $v_{\parallel}$ for these particles but the rate of increase is slowed due to pitch angle scattering which acts to keep $T_{\parallel} \approx T_{\perp}$. The increase in the current can be seen in Fig. 3. The cutoff at v_c is still being maintained but a few particles are accelerated to higher velocities.

Figure 6 shows the log of the electron distribution at t = 8800 ω_e^{-1}. A cold dense core of trapped electrons surrounded by the hot isotropic accelerated electrons is seen. This distribution has marked similarity to the auroral electron distributions measured by Kaufmann et al. [1978].

Conclusions

The acceleration in the auroral zones is, of course, a spatial problem. While temporal simulations such as reported here are very important for understanding the basic microphysics that takes place in the auroral environment, large scale macrophysics simulations are needed. The present results are a necessary input before a complete understanding of the total system dynamics can be gained. Development of such a capability is presently underway. We present below a qualitative picture of the macrostructure expected on the basis of our simulations. The first point is that for the pitch angle scattering to be effective requires $\Omega_e/\omega_e > 1$. Thus one would expect to see strong dc resistivity and parallel elecric fields between 2000 to 12000 km. The critical value of the current at which strong resistivity appears increases with Ω_e/ω_e. Thus, there exists a maximum critical current that can be carried along the field line. Below this level the ion cavities prevent the bulk of the electrons from being accelerated and tails of field aligned electrons are formed. However, when this critical current is exceeded one expects the emission of both upper and lower hybrid waves, large parallel electric fields, and a hot isotropized electron distribution with a cold dense core. The strongest resistivity and hence the largest electric fields will appear in the region where the current is clamped. One can make a rough estimate of the initial extent of this region by assuming $\Delta r = v\tau$ where v is the speed of the high velocity particles and τ is the time over which the current is clamped. For the simulation shown $\tau \approx 4.10^3\ \omega_e^{-1}$. Assuming $n_p \approx 100$ cm and a velocity of a keV electron this leads to a distance of 200 km. This is, of course, only a rough order of magnitude estimate but the main point is that the resistivity and the parallel electric fields should extend at least initially over a large region in comparison to the Debye length ($\approx$ 3m). This is in agreement with a recent analysis of satellite data of potential drops along auroral field lines [Mozer, 1981]. The dynamic spatial behavior depends upon how E_o arises and is a subject for further study but this region could shrink. For the simulation shown in detail $E_o = 2.7\times10^{-4}\ T_e^{1/2} n_p^{1/2}$ where T_e is in eV, n_p is plasma density in cm^3 and E_o is in V/m) for $t \geq 2000\ \omega_e^{-1}$. For T_e = 20eV and $n_p = 100$, $E_o \simeq 10^{-2}$ V/m and $\Delta\phi \simeq E_o \times \Delta r = 2$keV. Based upon our series of simulation $\tau \propto E_o^{-1}$. For constant $\Delta\phi$ reduction of Δr would lead to a larger E_o. This, in turn, would lead to a shorter τ and further reduction of Δr. On the other hand, if the system responds by raising ϕ in order to drive a $j > j_{cr}$, an increased E_o and a shorter Δr will result. Such questions can only be studied with a large scale transport code. Another spatial effect presently under study is the anomalous transport of the hot electrons across the magnetic field and out of the acceleration region. If this takes place at a fast enough rate such that $T_\perp$ remains less than $T_\parallel$ the current will remain clamped. In this case τ will be determined by the timescale for this perpendicular transport.

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