N93-23211
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(NASA-CR-192335) A PROPOSED NEUTRAL LINE SIGNATURE (Colorado Univ.) 22 p
IN-46-CR
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A PROPOSED NEUTRAL LINE SIGNATURE

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Submitted JGR

Abstract

An identifying signature is proposed for the existence and location of the neutral line in the magnetotail. The signature, abrupt density and temperature changes in the Earth-tail direction, was first discovered in test particle simulations. Such temperature variations have been observed in ISEE data (Huang et. al. 1992), but their connection to the possible existence of a neutral line in the tail has not yet been established. The proposed signature develops earlier than the ion velocity space ridge of Martin and Speiser (1988), but can only be seen by spacecraft in the vicinity of the neutral line, while the latter can locate a neutral line remotely.

INTRODUCTION

Since Dungey (1961) posed the problem of magnetic field line reconnection in the Earth's magnetotail a search has been on for a mechanism that would allow the release of the stored magnetic energy, leading to a magnetospheric substorm. The resistive tearing mode provides a natural mechanism for the release of the stored magnetic energy, but the resistive MHD simulations of Birn and Hesse (1990) show that the reconnection and plasmoid formation around the associated O-point develop on the time scale of substorm growth for magnetic Reynolds numbers $S = v_A L/\eta$ of the order of 100-200. Clearly a strong collisionless resistivity is required.

In the search for that resistivity two broad approaches can be identified: a search for a dynamical collisionless resistivity and a search for a turbulent collisionless resistivity. In the former, the finite coherence time (the time during which the current carriers are coherently accelerated by the electric field, also called the decorrelation time, or resistive time) arises from single particle dynamics in the magnetotail fields, while in the latter it comes from the scattering of the particles by the collective modes of the current carrying plasma. In either case, in order to provide the diffusion of the magnetic field, the effective resistivity needs to be large near the X-point, within a small area called the diffusion region or diffusion zone (eg. Lyons and Nishida, 1988; LaBelle and Teumann, 1988).

Several candidates have been proposed for a turbulent resistive time (eg. Hagege et. al., 1973; Huba et. al., 1978; Drake and Lee, 1977; Esarey and Molvig, 1987), but recent results form the ISEE-1 and ISEE-2 satellites on the CDAW-6 substorm (eg. Anderson, 1984) indicate that wave intensities in the current sheet are insufficient to account for the observed reconnection rate and, in addition, most wave intensities decrease dramatically at the center of the current sheet, making it even harder for turbulence to produce the required resistivity. It is also interesting to note that, in the related field geometry of the magnetopause, LaBelle and Treumann (1988) also note that plasma wave amplitudes are always too small to explain reconnection. Proposed candidates for a dynamical resistive time include inertial, or residence times (Speiser, 1970), gyroviscosity (Dungey 1988; Lyons and Pridmore-Brown 1990), and Coroniti's (1980) 'wave' induced pitch angle scattering. Coroniti, (1985) also used Speiser's (1970) inertial (or gyro) resistivity as the key dissipative element in his explosive substorm model. Recently, chaotic orbits of electrons (eg. Büchner and Zelenyĭ 1986,Martin 1986) and ions (Horton and Tajima 1991) have also been invoked to provide the necessary dissipation mechanism.

Many authors have studied in the past the dynamics of charged particles in tail-like fields (eg. Parker 1957; Speiser 1965, 1967, 1968, 1970; Schindler 1965; Sonnerup 1971; Eastwood 1972, 1974) but in recent years interest in single particle dynamics has increased considerably, with emphasis placed on either various forms of dynamical resistivity, or the effects of stochasticity on the evolution of the tail, especially the evolution of the particle distribution function (eg. Wagner et. al. 1981; Lyons and Speiser 1982; Kim and Cary 1983; Speiser and Lyons 1984; Chen and Palmadesso 1986; Martin 1986; Büchner and Zelenyĭ 1986, 1987; Doxas 1988). Recent numerical work on the latter has been particularly fruitful, with numerical results in good agreement with some observational data (Martin and Speiser 1988; Speiser et. al. 1991; Doxas et. al. 1990; Burkhart and Chen 1991; Chen et. al. 1990).

Chen and Palmadesso (1986) first studied in detail the chaotic dynamics of charged particles in a simple two dimensional magnetotail model (a Harris sheet with a small normal field component), and Burkhart and Chen (1991) discovered the $H^{1/4}$ scaling of the resonant energies for that system. Subsequent comparison of their results with observational data from the ISEE 1 spacecraft (Chen et. al. 1990) identified this scaling in quiet-time central plasma sheet distribution functions. Doxas et. al. (1990) advanced ensembles of particles in a model of the reconnecting magnetotail fields by adding a simple tearing mode perturbation to the model used by Chen and Palmadesso (1986), and observed the evolution of particle density, temperature, current and streaming velocity. The numerical results were again in good agreement with observations, despite the simplicity of the model and the fact that no microscopic collective effects were included in the simulations. It should be noted here that both Doxas et. al. (1990) and Chen (1991) found that their results persisted even in the presence of considerable velocity-space scattering. Finally Martin and Speiser (1988) discovered an energetic ion signature of the neutral line in their test particle simulations of a simple X-type magnetic field model. The signature was subsequently seen in observational data from the ISEE-1 satellite.

The above results, all of which were obtained by following the motion of test particles in simple magnetotail models, suggest that single particle dynamics play an important role in the development of the tail, possibly along the lines suggested by Horton and Tajima (1988) where the large scale field structure in the tail is determined by the Earth-solar wind interaction, magnetic reconnection is driven, and local plasma instabilities couple to the driving. In that case the observed particle distributions would be mostly determined by the motion of the particles in the fields derived from the (resistive) driven MHD dynamics, consistent with the fact that test particle simulations give such realistic results.

Encouraged by these recent theoretical, numerical and observational developments, we suggest here a second possible signature for the neutral line, first seen in our numerical calculations, namely abrupt temperature and density variations in the Earth-tail direction. Such variations were recently observed in satellite data of the central plasma sheet (Huang et. al. 1992) but their connection to the possible existence of a neutral line remains to be determined.

We also show that tearing-like time-dependent fields produce a qualitatively different density and temperature pattern than do time-independent fields. The latter heat the plasma symmetrically around the neutral line, and do not produce a pronounced density drop tailward of it. Time-dependent fields produce a characteristic particle depletion tailward of the neutral line, and asymmetric plasma heating. Our simulations also suggest that the heating mechanism is qualitatively different for systems with or without a neutral line. When a neutral line is present the temperature $(< \Delta v^2 >)$ rises as time squared, reminiscent of the accelerator modes of the standard map. When no neutral line is present, the temperature rises linearly with time $(\langle \Delta v^2 \rangle \sim t)$ in a manner characteristic of true diffusion.

2. Particle Dynamics in Reconnection-like Fields

We model the electric and magnetic fields in the geomagnetic tail by a Harris sheet with a small northward magnetic field component, and we add a reconnection type perturbation of wavenumber k in the Earth-tail direction, and growth rate γ. The growing perturbation models the dynamics given by resistive MHD simulations of the magnetotail (eg. Birn and Hesse 1990; Steinolfson and Van Hoven 1984). The fields are given by

$$
\begin{aligned}
B_x &= B_0 \tanh\left(\frac{z}{a}\right) \\
B_z &= B_0 b_0 + B_0 \psi_0 k \sin(kx) e^{\gamma t} \\
E_y &= B_0 \psi_0 \frac{\gamma}{c} \cos(kx) e^{\gamma t}
\end{aligned}
\tag{1}
$$

with x, y, z the usual magnetotail coordinates. These fields can be derived from the magnetic flux function

$$
\psi = B_0 [a \ln(\cosh(z/a)) + \psi_0 \cos(kx) e^{\gamma t} - b_0 x] \tag{2}
$$

where the vector potential is $\vec{A} = -\psi(x, z, t)\hat{e}_y$ and the fields are given by $\vec{B} = \hat{y} \times \nabla\psi$ and $E_y = (1/c)\partial_t \psi$. In the above expressions B_0 is the magnitude of the asymptotic (far from the neutral sheet) horizontal field, a the scale length of the horizontal field, b_0 the normal (northward) magnetic field component, ψ_0 is the amplitude of the tearing perturbation, γ its growth rate and k its wavenumber. We place the origin of the x-axis at the asymptotic position of the neutral line (at $t \to \infty$), so that the Earth lies in the positive x direction, and the negative x direction is tailward (cf. Fig. 1). A neutral line first appears at $kx = -\pi/2$ when B_z first turns southward, at time $t = t_c$

$$t_c = \frac{1}{\gamma} \ln \left(\frac{b_0}{k\psi_0} \right) \qquad (3).$$

For $t \ll t_c$ the field lines are long, open loops, similar to the parabolic field lines of Kim and Cary (1983) and the widely studied time-independent two-dimensional field configuration (eg. Speiser, 1965, 1967, 1968; Chen and Palmadesso, 1986; Büchner and Zelenyĭ, 1986, 1989). For $t > t_c$ there is an O-line tailward of $kx = -\pi/2$, which will asymptotically reach the position $kx = -\pi$ as $t \to \infty$, and an X-line Earthward of $kx = -\pi/2$, moving toward $x = 0$ as $t \to \infty$ (cf. Fig. 1b).

The particles are advanced in time using the fields given in Eq. (1), and particle density, temperature current and bulk velocities, are measured as a function of x and z at different times during the run. Our results show the neutral line playing an important role in the development of the tail, with most changes in particle temperature, density and current occurring in its spatial and temporal vicinity. We briefly describe the general results here, but refer the reader to Doxas et. al. (1990) for more details of both the method and the results.

For $t - t_c \ll -1/\gamma$, when the fields are still a good approximation to the unperturbed two-dimensional case, we find that, although some current is flowing in the current sheet and the plasma temperature is somewhat higher than at $t = 0$, the initial distribution changes little until the neutral line appears. Shortly before the neutral line is formed (in general 1–2 *min*) the number density drops in the area where the X-point is going to appear and increases just earthward of that point (eg. Fig. 2b), a narrow channel of cross-tail current, in phase with the electric field ($j_y E_y > 0$), is formed around the X-point and the temperature increases in the same narrow channel where the cross-tail current flows, with maximum observed temperatures in the range 0.1–0.6 keV (Fig. 2c). Heating in the x-direction (Earth-tail) is confined to Earthward of the point where the neutral line is about to form (cf. Fig. 2d). Finally, shortly after the neutral line appears (in general 2–3 min later) the density increases even further just earthward of the neutral line while dropping considerably in the tailward direction, and the plasma in the current sheet reaches temperatures in the range 0.5–1.2 keV. The heating is still confined to Earthward of $kx = -\pi/2$, where the X-line first appeared.

The results we obtain with the above model for the temperature, density and bulk flow velocities in both the central plasma sheet and the Plasma Sheet Boundary Layer (PSBL) are in good qualitative and quantitative agreement with observations (see Doxas et. al. 1990 for a more detailed comparison to observations) although, to our knowledge, no observational evidence existed at the time for a sharp temperature and/or density gradient in the Earth-tail direction which could be associated with the formation of a neutral line as our simulations suggest. Recently however, Huang et. al. (1991) reported observing 'dramatic' nonadiabatic heating of the central plasma sheet and PSBL. This considerable and sudden increase of the plasma temperature is in good agreement with our results, both in timing and in magnitude, and encourages us to suggest that a sharp temperature gradient does indeed accompany the formation of a neutral line, with the temperature increase confined to Earthward of the neutral line. This gradient would then be a signature for the detection of a neutral line in the tail according to the model presented here.

3. Time Independent Neutral Line

To more clearly illustrate that the asymmetric temperature and density profiles are a signature of the neutral line produced by a tearing like perturbation, we also investigated the evolution of ensembles of particles in a time independent neutral line, where the electric field is a uniform cross-tail DC field. The fields are now given by

$$\begin{aligned} B_x &= B_0 \tanh\left(\frac{z}{a}\right) \\ B_z &= B_0 b_0 + B_0 \psi_0 k \sin(kx) \\ E_y &= const. \end{aligned} \tag{4}$$

which are the same as the fields in Eq. 1 with $\gamma = 0$ and a DC electric field added. The full dynamics of charged particles in the vicinity of a time independent neutral line have been studied in the past (eg. Martin 1986), and are beyond the scope of the present work. Here we will describe the part of our results which is relevant to the neutral line signature that we propose.

Figure 3 shows the particle number density and temperature as a function of x and z for a simulation with time independent fields. Figure 4 shows the number density and temperature for a similar run with a tearing type perturbation. The cross-tail DC electric field in the time independent run was chosen to be approximately equal to the average electric field in the time dependent run, and the plots were made after the same length of integration, approximately 3 minutes. In both runs the value of the asymptotic magnetic field is B_0 =20 nT, and the ratio $b_0 = B_z/B_0$ is $b_0 = 0.05$. In the time independent run the amplitude of the perturbation is $\psi_0 = 0.06$, and is of course constant in time, while in the time dependent run it is initially $\psi_0 = 0.04$, and grows to $\psi_0 = 0.06$ at the end of the run. The growth rate is $\gamma = 0.001$ (the ion gyrofrequency in the asymptotic field, $\omega_{ci} = eB_0/mc$, is unity).

The two runs produce qualitatively different density and temperature profiles, which, coupled to B_z measurements, should allow us to infer the existence and position of a neutral line. The time independent fields produce an almost homogeneous heating and density increase throughout the $z = 0$ plane, while the tearing type fields produced sharp temperature and density gradients, with all heating confined to earthward of the neutral line, and a characteristic depletion in the particle number density just tailward of it. A satellite would therefore see the passage of a tailward traveling neutral line as a sharp drop in the particle number density followed by a region of high temperature plasma. Such events have been reported by Huang et. al. 1992, but their connection to the existence of a possible neutral line remains to be determined.

Our simulations also show that the heating mechanism is qualitatively different for systems with and without a neutral line. The point is best illustrated by Fig. 5, where we plot the temperature of the plasma in the vicinity of the neutral line against time. Before the appearance of the neutral line, the temperature (which is a measure of the square velocity spread of the particles $< \Delta v^2 >$) increases linearly in time, which suggests a diffusive process. After the appearance of the neutral line, the temperature rises as time squared, which implies a heating mechanism that relies on free acceleration, reminiscent of the accelerator modes of the standard map. Note that the temperature actually rises as $t + t^2$, which means that both diffusive and acceleration heating are taking place at the same time, but the t^2 scaling will of course dominate eventually. These results are in agreement with our previous observation (Doxas et. al. 1990) that most of the heating occurs after the appearance of the neutral line.

4. Discussion and Summary

In this work we propose a second neutral line signature, namely the occurrence of sharp temperature and density gradients in the vicinity of the neutral line, with heating confined mostly to the earthward side of the line. The proposed signature was discovered in test particle numerical simulations, in which ensembles of charged particles are advanced in a simple two-dimensional time-dependent model of the magnetotail, with a tearing mode perturbation providing the neutral line. By using a tearing mode perturbation, the self consistency required on the scale of resistive MHD dynamics is included in the model, although the microscopic dynamics observed is solely the result of single particle motion. Despite the simplicity of the electromagnetic field model used, our confidence in the relevance of our results is, we believe, justified by the good qualitative and quantitative agreement with observations.

The signature we suggest is more sensitive than that of Martin and Speiser (1988), in the sense that it is detectable much sooner, but it is local in nature (the spacecraft must be in the vicinity of the neutral line) in contrast to that of Martin and Speiser (1988) which can deduce the position of the neutral line from measurements of the velocity distribution function taken above the central plasma sheet. Just how close the spacecraft must be to detect the density and temperature variations remains to be determined by further investigation, and depends on the strength $\delta B_z/B_{x0}$ and wavelength λ of the reconnection event.

The formation of a neutral line in the geomagnetic tail plays of course an important role in a number of substorm theories, and its existence and position has been traditionally infered by changes in the direction of the normal magnetic field component. Since neutral lines are notoriously difficult entities to observe however, any additional way of locating one would be very welcome. Such a neutral line signature was first discovered in test particle simulations of an isolated neutral line by Martin and Speiser (1988), who observed a ridge-like structure in the velocity distribution of energetic ions sampled above and earthward of the neutral line. Because of the existence of a neutral line, in the vicinity of which $B_z \to 0$, some of the particles that interact with the current sheet will not be turned around by B_z. The particles going through the current sheet without being turned by B_z come from a smaller part of the initial distribution, generating the ridge in the distribution function

(Martin and Speiser 1988). Subsequent search of the ISEE-1 satellite data revealed the existence of such a structure (Speiser et. al. 1991) which would allow the remote detection of a neutral line. Note that such a structure is also observed in our simulations (cf. Fig. 6), giving us additional confidence in the relevance of our results.

The temperature and density gradients that we propose here as possible additional neutral line signatures, are more sensitive tests than the ridge structure of Martin and Speiser (1988). We observe the ridge structure in our simulations only in the cases where a well developed neutral line exists (or alternatively several minutes after its appearance), while the temperature and density gradients become pronounced much earlier (approximately 1-4 min earlier), even as early as shortly *before* the formation of the neutral line. On the other hand, the ridge signature allows us to locate the neutral line remotely, while the temperature signature requires that the satellite be in its spatial vicinity, making detection more difficult.

We hasten to add at this point that the present account of the dynamics seen in the simulations is considerably simplified. The case of the temperature (or number density) as a signature for the neutral line for instance, is not as clear cut as one might infer by looking at Fig. 2. In Fig. 7 we show the particle temperature for two similar runs. We see that in Fig. 7b the heating is not strictly confined to earthward of the neutral line as is in Fig. 7a, but has also spilled a bit tailward, although there is still a very abrupt change. Three of our twenty runs exhibit such a feature, and the cause is not readily apparent; the values of most parameters for those runs are very close to the values of runs that show behaviour identical to Fig. 2. So although the overall qualitative picture that emerges from the simulations is insensitive to initial conditions, the detailed dynamics observed is very complex. Those two properties, exhibited not only by the temperature but by all observables we follow, are the hallmark of deterministic stochastic systems. A degree of variability in the details of the final state is therefore an encouraging feature of the numerical results. The magnetotail itself exhibits such behaviour, and it has often been characterized in the literature as 'chaotic' or 'highly turbulent', turbulence being the most readily available explanation for such an apparently random behaviour.

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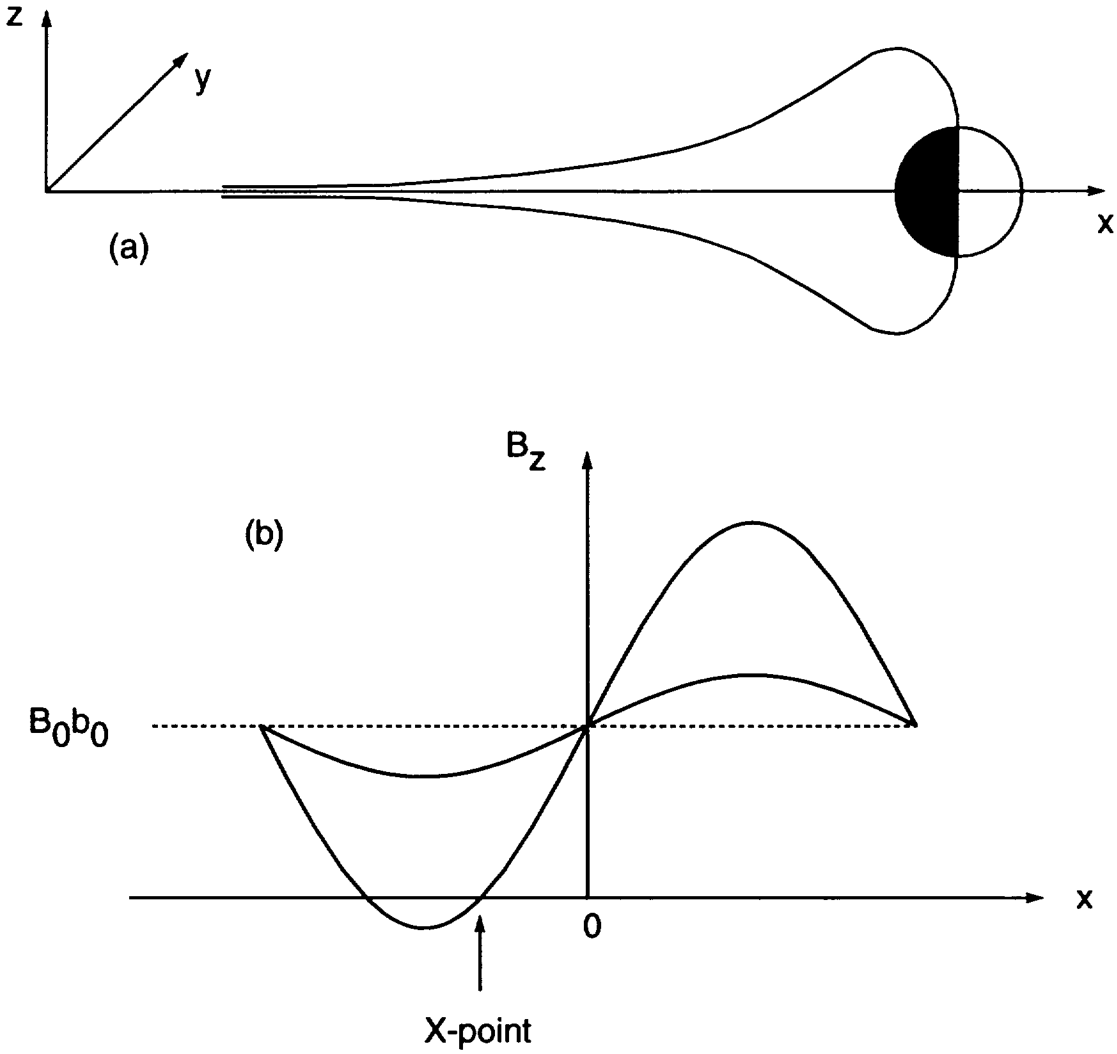

Figure 1

The fields described by Eq. 1.

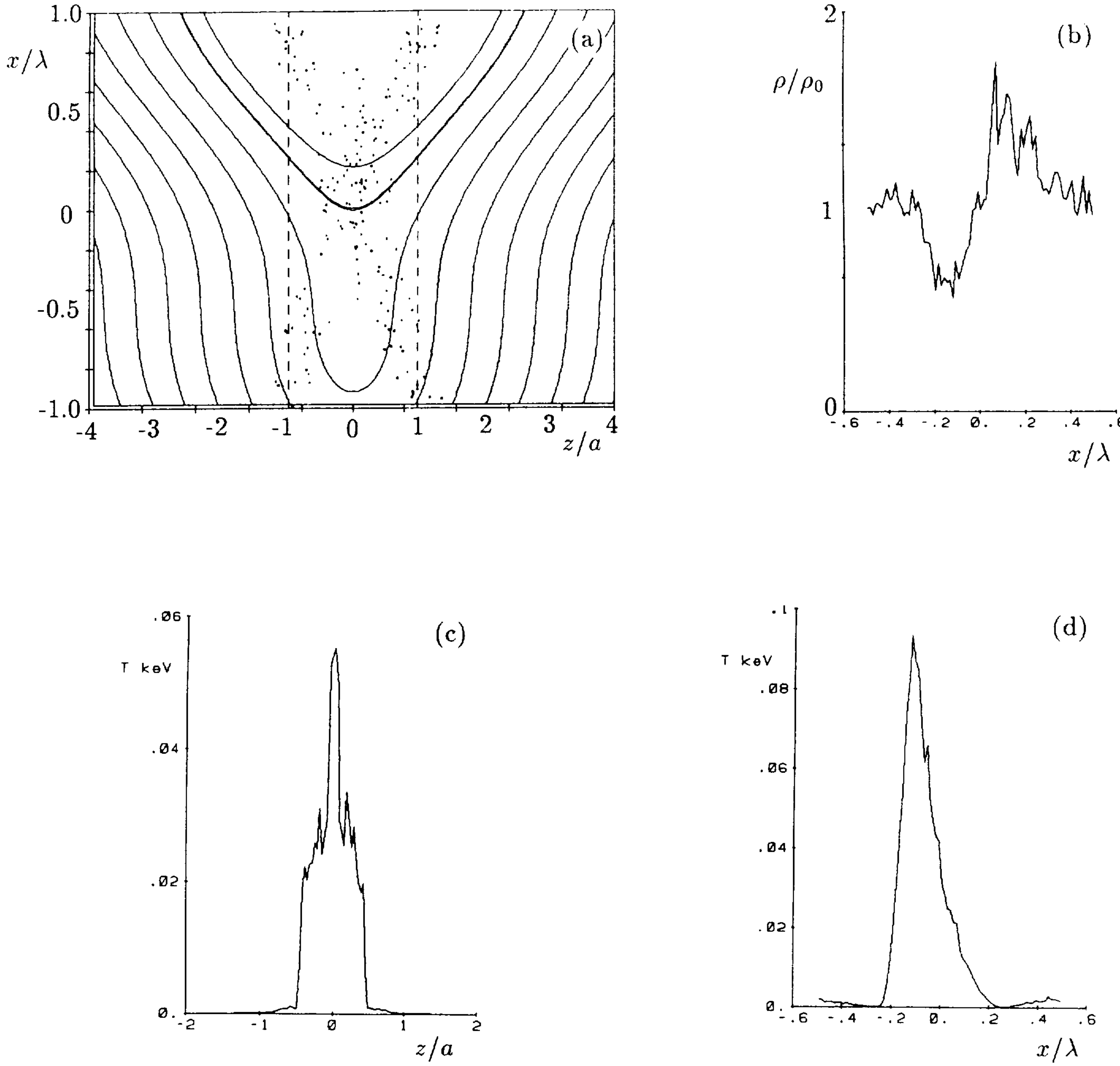

Figure 2

a) A contour plot of the magnetic flux function (Eq. 2), with a sample 200 particles superimposed. The Earth is at the top of the figure.

b) The number density as a function of x.

c) The particle temperature as a function of z.

d) The particle temperature as a function of x.

The time is approximately 1 *min* before the formation of the neutral line.

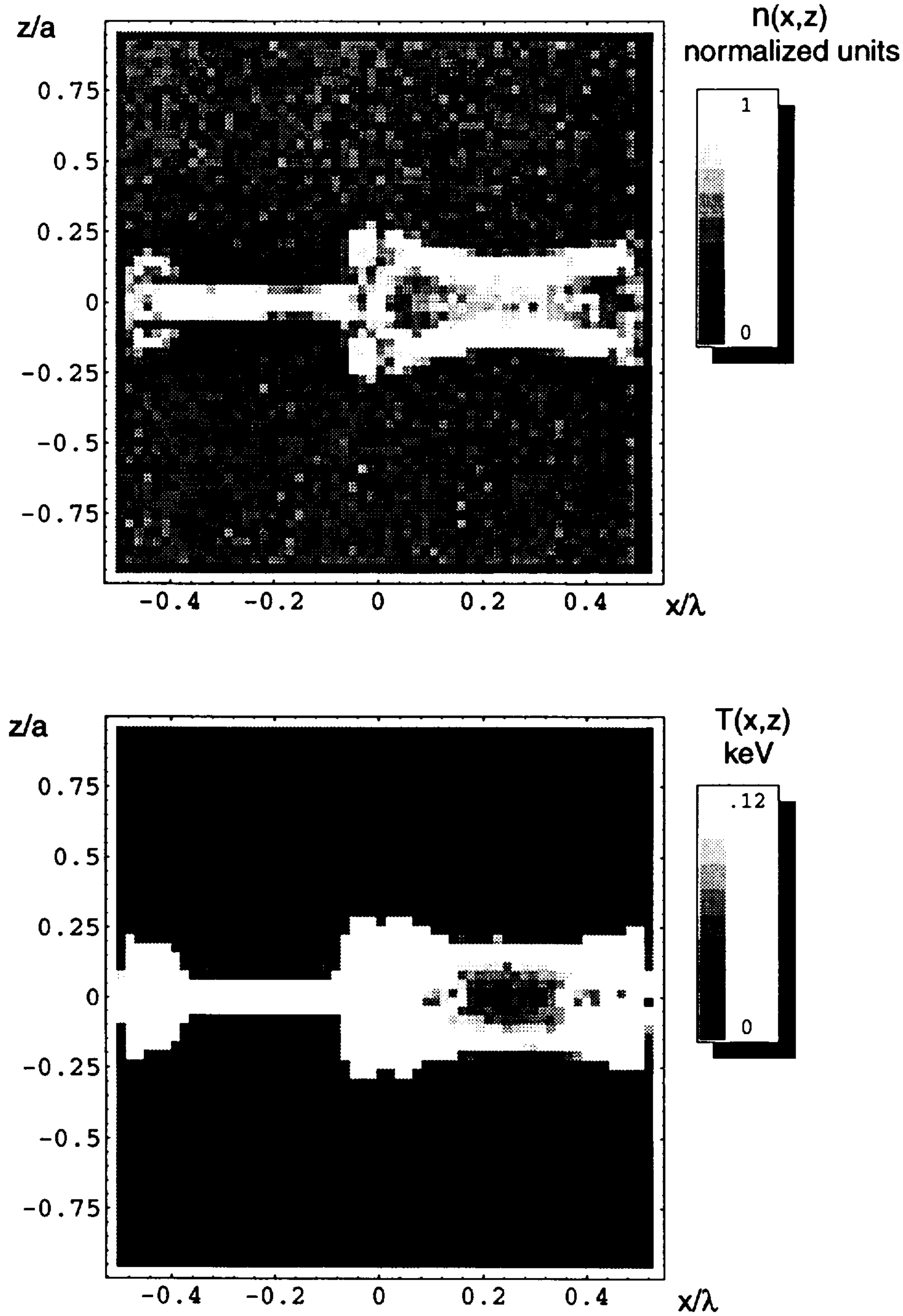

Figure 3

The number density and temperature plotted against x and z for the time independent case. Heating occurs throughout the $z = 0$ plane.

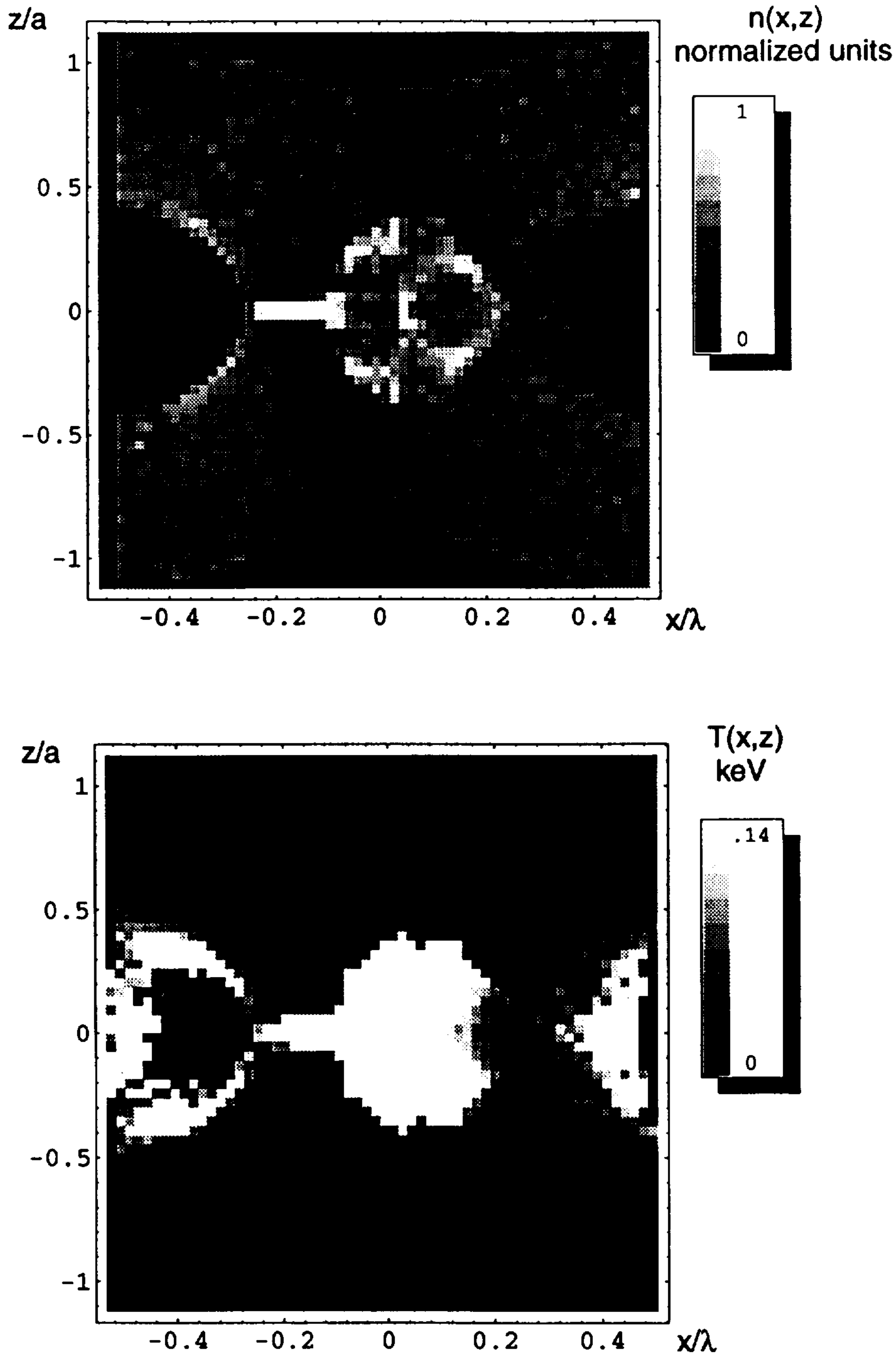

Figure 4

The number density and temperature plotted against x and z for the time dependent case. Heating is confined to earthward of the neutral line, which at this time is approximately at $x/\lambda = -.22$. A characteristic low density region is formed tailward of the neutral line.

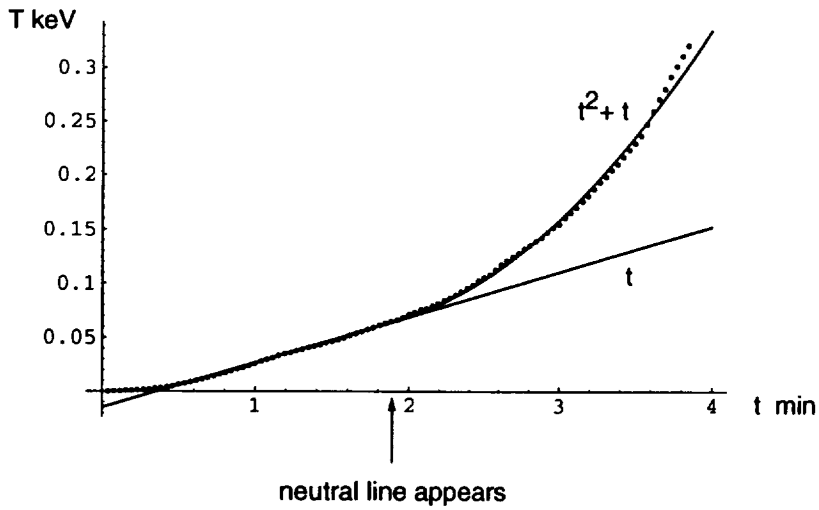

Figure 5

The temperature of the plasma in the vicinity of the neutral line plotted against time for the time dependent case. We plot the average temperature of particles in the region $-.35 < x/\lambda < -.15$, $-.25 < z/a < .25$.

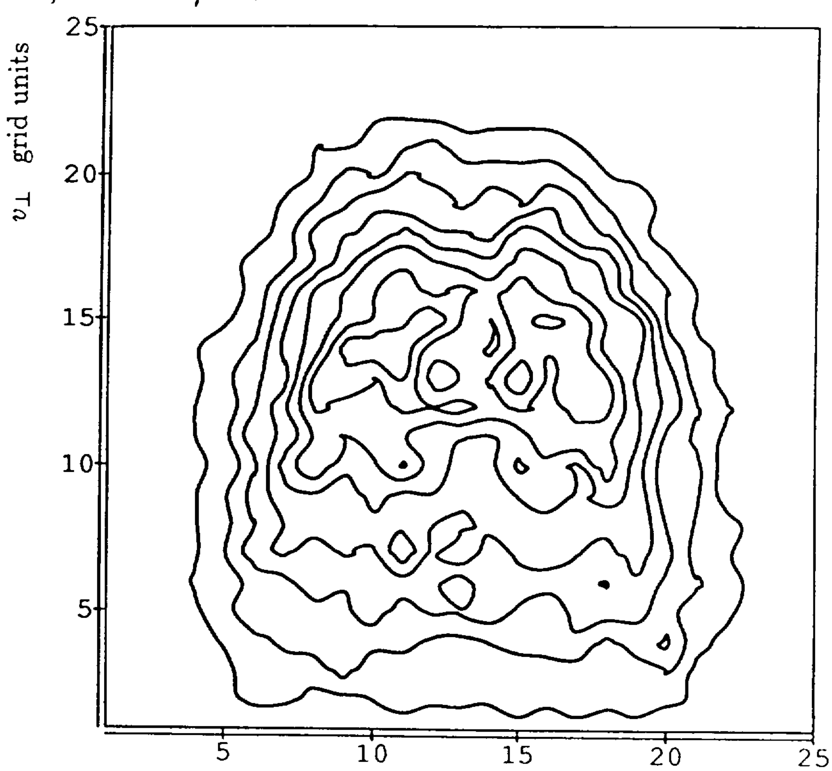

Figure 6

$v_\parallel$ grid units

A contour plot of the particle distribution function, showing the 'ridge' neutral line signature (Martin and Speiser, 1988). The time in this figure is approximately 5.5 *min* after the appearance of the neutral line. A DC electric field of 0.2 mV/m is also present across the tail.

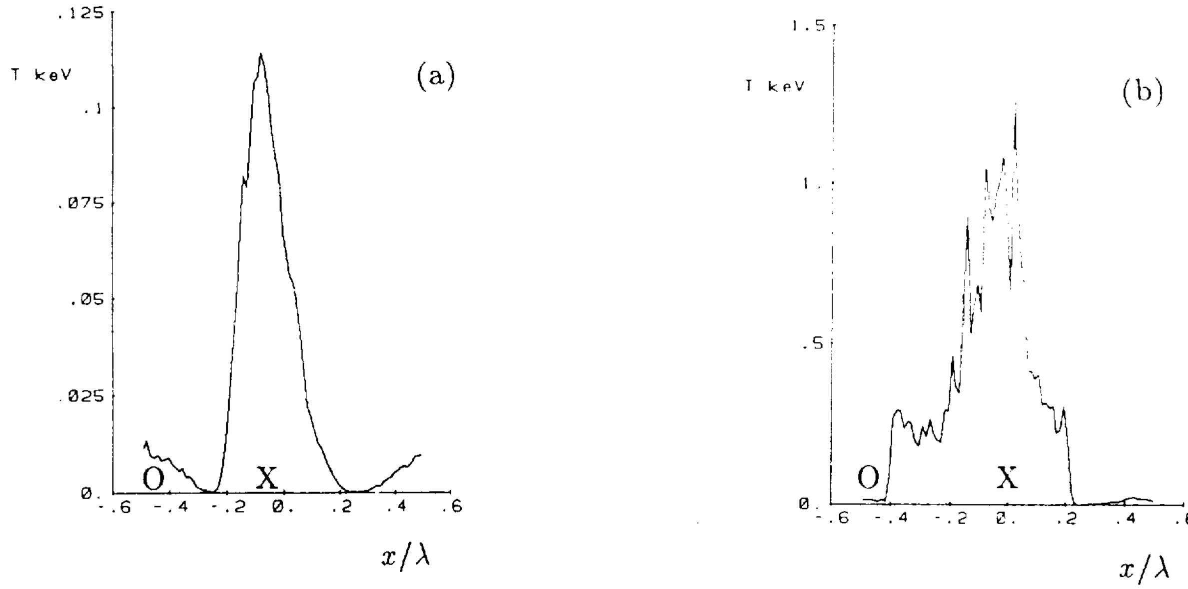

Figure 7

The plasma temperature plotted as a function of x for approximately the same time ($\sim$ 0.3 *min* after the appearance of the neutral line) for two similar runs. The only difference between the initial conditions was a slightly higher initial temperature and mode amplitude for **(b)**.