A SHORT WAVELENGTH INSTABILITY IN THE NEUTRAL SHEET OF THE EARTH'S GEOMAGNETIC TAIL

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Abstract. In an earlier paper, Bowers (1973), ion plasma oscillations were found to be unstable in the steady state developed by Cowley (1972) for the neutral sheet in the Earth's geomagnetic tail. In this paper a similar stability analysis is carried out but for a different steady state, suggested by Dungey, with the result that unstable waves with frequencies near the electron plasma frequency are found. In the Dungey steady state the current necessary for magnetic field reversal is carried by plasma originating from both the magnetosheath and the lobes of the tail. This modifies the steady state proposed by Alfvén and subsequently developed by Cowley in which all the current is carried by plasma from the lobes of the tail thereby fixing the cross-tail potential \( \Phi \). With magnetosheath plasma present the value of \( \Phi \) is no longer fixed solely by parameters in the lobes of the tail but the cross-tail electric field is still assumed localised in the dusk region of the sheet as in the Cowley model due to the balance of charge required in the neutral sheet. The value of \( \Phi \) can be expected to increase as magnetic flux is transported to the tail which inflates and causes flux annihilation because the magnetosheath plasma in the neutral sheet has insufficient pressure to keep the two lobes of the tail apart. The Vlasov-Maxwell set of equations is perturbed and linearised enabling a critical condition for instability to be found for modes propagating across the tail. Typically, this condition requires \( \epsilon \Phi \gtrsim KT_m \) where \( T_m \) is the temperature of magnetosheath electrons. The instability occurs in the presence of cold plasma which has \( E \times B \) drifted into the neutral sheet from the lobes of the tail. This contrasts with the usual two stream instability which is stabilised by the cold plasma. Once precipitated the instability may be explosive provided current disruption occurs, for then a further increase in \( \Phi \) will result which drives a greater range of wave numbers unstable thereby causing even more turbulence and an even larger cross-tail electric field. Because of this behaviour the instability may be a trigger for a substorm.

List of Symbols

\( \Phi \) total cross-tail potential (throughout the paper this potential is assumed to be localised to the dusk side of the neutral sheet).

\( \phi \) steady state potential for a normal electric field which is assumed to exist in the region of interest for this paper (region 2 in Figure 1).

\( \xi \) total energy of a particle in the steady state.

\( \vec{p} \) cross-tail canonical momentum of a particle in the steady state.

\( m \) particle mass (the superfixes \( i \) and \( e \) denote proton and electron respectively).

\( \nu \nu_m V \) the thermal speeds of electrons from the lobes of the tail, magnetosheath electrons and magnetosheath protons respectively.

\( \vec{V} \) the average cross-tail speed attained by electrons due to acceleration – in the neutral sheet – by the cross-tail electric field, i.e. \( \frac{\text{d}r}{\text{d}t}(2\vec{V})^{-1} = e\Phi \).

\( \omega_{1p}, \omega_{2p}, \omega_{3p} \) neutral sheet plasma frequencies for electrons originating from the polar wind, dusk magnetosheath and dawn magnetosheath respectively.

\( \omega_{1p} \) neutral sheet plasma frequency of protons.

\( \omega \) wave frequency.

\( k \) wave number in the \( y \)-direction.

\( l \) typical wave number in the \( z \)-direction.

\( L_z \) scale length for variation of the wave field with \( z \).

\( c \) velocity of light.

\( q \) the modulus of \( v_z \).

Dashes denote wave quantities although later in the paper the dash on \( E_y \), the wave electric field in the \( y \)-direction, is omitted.
1. Introduction

This paper considers a simple model, for the $x$-type neutral line in the Earth’s geomagnetic tail, in which the neutral line becomes a neutral sheet separating the two lobes of the tail containing oppositely directed straight lines of force. When the current in the neutral sheet is carried only by cold plasma $E \times B$ drifting into the sheet from the lobes of the tail, Alfvén (1968) showed that the necessary potential drop across a uniform tail is given by

$$e\Phi = \frac{B^2}{4\pi n},$$

where $n$ and $B$ are the density and magnetic field strength far from the neutral sheet. This model was modified by Cowley (1972) who pointed out that a uniform electric field would mean protons spending far longer in the neutral sheet than electrons because of their greater mass, leading to a charge imbalance. In Cowley’s model the same potential drop is localised in the dusk region of the sheet causing the protons to travel a smaller distance than the electrons in the neutral sheet thereby correcting for any charge imbalance. In the rest of the neutral sheet there is no cross-tail electric field because the electrons have been energised at the dusk side and possess sufficient pressure to prevent the magnetic field from annihilating in the sheet. In the region free from cross-tail electric field a one dimensional steady state can be constructed which is inhomogeneous only in the direction normal to the neutral sheet. Using such a steady state Bowers (1973) – henceforth referred to as Paper I – was able to consider the stability of the energised electrons in the neutral sheet to waves travelling across the tail. Ion plasma oscillations were found to be unstable but they were driven by that part of the electron distribution which carried the least current and for that reason cannot be expected to lead to significant current disruption. In fact the type of electron distribution in the neutral sheet expected from the Cowley model turned out to be remarkably stable to short wavelengths because of the large spread in velocity along the direction of current flow.

In reality plasma must come in from the magnetosheath along the flanks of the tail. Indeed, if the magnetosheath plasma in the neutral sheet has sufficient pressure to balance the magnetic pressure of the tail no cross-tail electric field is needed and so no field annihilation will occur. Recently, Dungey (1972) pointed out that the magnetosheath exerts a pressure, on opposite sides of the neutral sheet, which tends to force the two lobes of the tail together. In particular, for a flared tail the magnetosheath plasma exerts such a pressure due to its streaming motion, in addition to the usual pressure due to temperature. Now in the neutral sheet the pressure of magnetosheath plasma, originating from the flanks of the tail, is due to temperature only and therefore would be insufficient to prevent magnetic field annihilation in the neutral sheet. Thus, in a flared tail a cross-tail electric field seems plausible. The cross-tail potential may well build up after the interplanetary magnetic field develops a southward component and leads, in the open model of the magnetosphere (Dungey, 1961), to erosion