Non-Stochastic Accelerartion of Protons in the Magnetic Neutral Sheet

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Abstract

A rapid non-stochastic proton acceleration mechanism by electrostatic waves during substorm activity in the magnetospheric tail is presented to explain the origin of energetic protons (up to Mev). The protons are accelerated normal to the neutral sheet. Near a reconnection point, however, the protons are also accelerated along the sheet by a second step process.

Introduction

During a substorm activity, high energy (up to Mev) protons are observed in the distant tail (Sarris et al., 1976). Zeleney et al., (1982) considered the proton acceleration by an inductive electric field near X-point of the magnetic field during the nonlinear tearing mode instability in the tail current sheet.

Gurnett et al. (1976) observed electrostatic waves propagating almost perpendicular to the local magnetic field, whose frequency range is the local lower hybrid resonance frequency with a typical electric field strength of about 1~5mV/m. These noises are closely related with large plasma flow velocities and in a few cases the noises are found to have particularly large intensities directly in the region vhere a magnetic reconnection and a charged particle acceleration are taking place. Cattell and Mozer (1982) also report that instantaneous field magnitudes rise up to 30mV/m when a substorm is active.

In this letter we present a very rapid proton acceleration mechanism by an electrostatic wave with a frequency near the lower hybrid resonance one during the reconnection phase near the tail neutral sheet. The proton acceleration mechanism we here consider has been investigated in a homogenous plasma by Sagdeev and Shapiro (1973), Sugihara and Midzuno (1979) and Dawson et at. (1983).

The physical mechanism of the acceleration process is as follows: The protons initially trapped in the electrostatic wave propagating perpendicular to the magnetic field move together with the wave, and are accelerated parallel to the wave front by the force of $\vec{V}_{ph}\times\vec{B}/c$($\vec{V}_{ph}$is the phase velocity of the wave). Note that the force acting on the protons is dc, which makes clear contrast to usual stochastic accelerations. The trapped protons become detrapped when the e $\vec{V}\times\vec{B}/c$ force exceeds the electrostatic force, e$\vec{E}$, of the wave. The characteristic acceleration time τ_A is given by $\tau_A\sim\omega_c^{-1}V_{max}/V_{ph}$, where ω_C is the proton cyclotron frequency, V_{max} the maximum velocity of the proton by this acceleration process, which is estimated as $V_{max}=cE/B$. The time τ_A is very rapid which is usually of the order of $2\pi/\omega_C$.

Equation of Motion for a Proton in the Neutral Sheet

We examine this acceleration mechanism in the neutral sheet by solving the equation of motion for a proton. The magnetic field configurations we here consider are schematically

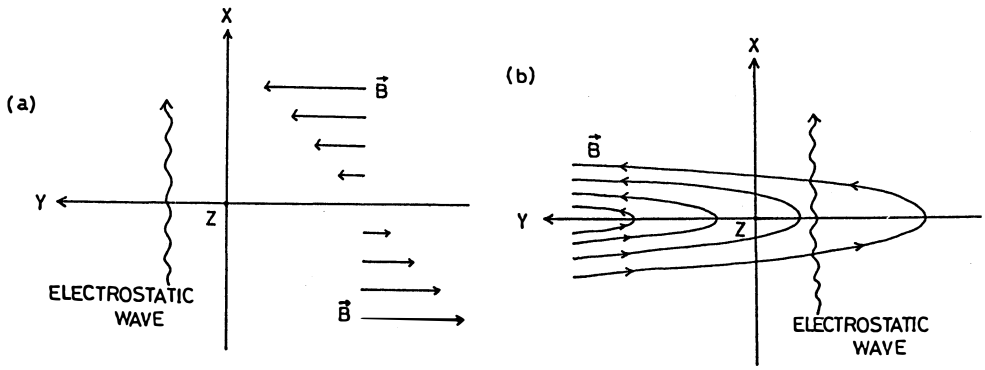

Fig. 1 Sketch of (a) $B_n=0$ and (b) $B_n\fallingdotseq 0$ magnetic field in the tail. The electrostatic wave propagates in the x direction.

drawn in Fig. 1, where in (a) the normal magnetic field component $B_n\vec{e}_x$ is zero and in (b) there exists a weak normal component, the configuration of which is more alike the magnetospheric tail near the X-point. In the latter case, the magnetic field is given by

$$\vec{B}=B_n\vec{e}_x+B_\infty\tanh(X/a)\,\vec{e}_y, \quad \cdots\cdots(1)$$

where a is the thickness of the current sheet and B_n is constant.

We assume the electrostatic wave, $E_x\sin(KX\text{-}\omega t)$, propagating across the current sheet in the positive × direction. Tue equations of motion for a proton are

$$\dot{V}_x=(eE_x/m)\sin(kX-\omega t)-\omega_c V_z\tanh(X/a), \quad \cdots\cdots(2)$$
$$\dot{V}_y=\omega_{cn}V_z, \quad \cdots\cdots(3)$$
$$\dot{V}_z=\omega_c V_x\tanh(X/a)-\omega_{cn}V_y, \quad \cdots\cdots(4)$$

where $\omega_c = eB_\infty/mc$ and $\omega_{cn} = eB_n/mc$. The above equations may be rewritten in the wave frame moving with the phase velocity of the wave. The nondimensional equations are

$$\ddot{\xi} = \varepsilon \sin \xi - K\dot{Z} \tanh [(\xi + WT) /K] , \quad \cdots\cdots (5)$$

$$\ddot{Y} = \varepsilon_n \dot{Z} \quad \cdots\cdots (6)$$

$$\ddot{Z} = K^{-1} (W + \dot{\xi}) \tanh [(\xi + WT) /K] - \varepsilon_n \dot{Y}, \quad \cdots\cdots (7)$$

where the lengthes, time T and velocities are nomalied by a, ω_c^{-1} and the proton thermal velocity V_t, respectively, and $K = ka$, $W = \omega/\omega_C$, $\varepsilon_n = K\ V_{max}/V_t$ ald $\varepsilon_n = B_n/B_\infty$.

At first we examine the case of $\varepsilon_n = 0$.

We consider a proton initially trapped in a potential well of the electrostatic wave and we choose $\dot{\xi} = 0$ at $T = 0$. From eq. (7) the proton is accelerated as it sees $\vec{V}_{ph} \times \vec{B}$ (dc) electric field and the proton velocity in the Z direction increases linearly with time. As time elapses the second term in the right hand side of eq.(5) becomes large and finally overcomes the electrostatic

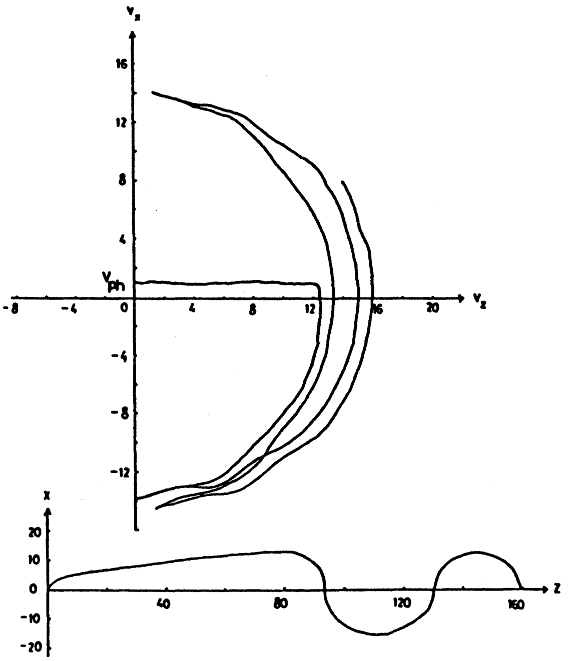

Fig. 2 Velocity-space orbit (upper) of a proton and orbit in the neutral sheet ($B_n = 0$). $V_{ph} = 1$, $V_{max} = 15$, $K = 10$, $W = 10$. The proton is initially trapped and $V_z(0) = 0$. After detrapping from the potentinl wall, the proton moves crossing the neutral sheet.

force of the wave, then the proton detraps. In Fig. 2 a typical example is shown for a proton which initial position is $X = Z = 0$ and $V_Z(0) = 0$. The parameters chosen are $\varepsilon = 150$, $K = 10$, $W = 10$, $V_{ph} = 1$. The maximum velocity $V_{max}$is 15 in the scale of V_t.

Figure 2 shows that the velocity at the point of detrapping is 12.4 and a little bit smaller than 15.

The characteristic acceleration time is $\tau_A = V_{max}/V_{ph} = 15$. The computational result is about 13.4. After detrapping from the electrostatic wave potential, the proton moves crossing the neutral sheet shown in the lower part of Fig. 2, and may be accelerated stochastically.

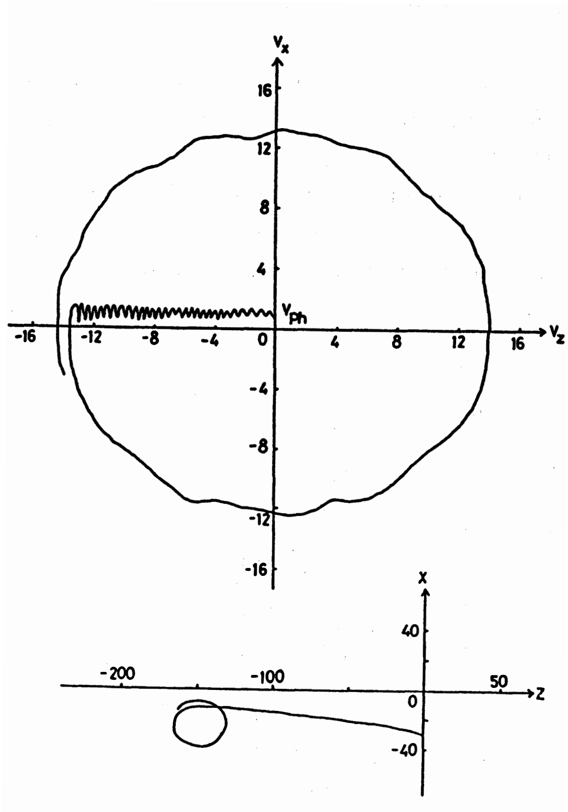

Fig. 3 Velocity-space orbit (upper) of a proton and orbit ($B_n = 0$).
$V_{ph} = 1$, $V_{max} = 15$, $K = 10$, $W = 10$. The proton is initially trapped and $V_z(0) = 0$. After detrapping from the potential well, the proton drifts across the magnetic field.

In Fig. 3 an example of the motion of proton which initial position is far from the neutral sheet is shown. After detrapping from the potential well the proton moves drifting across the magnetic field.

Next we consider the case where a weak normal magnetic field exists in the x direction as shown in Fig. 1(b). When ε_n is very small, the linear acceleration in the Z direction can still occur as seen from eq. (7). An example in the case of $\varepsilon_n = 0.1$ is shown in Fig. 4. From eq. (6) the proton is accelerated in the positive Y direction. The maximum velocity in the Z direction becomes a little bit smaller than that in the case of $B_n = 0$, and the proton does not detrap from the electrostatic potential well. After the first step acceleration a second step acceleration in the
19 Y direction, namely along the main magnetic field can occur, Such a second step acceleration

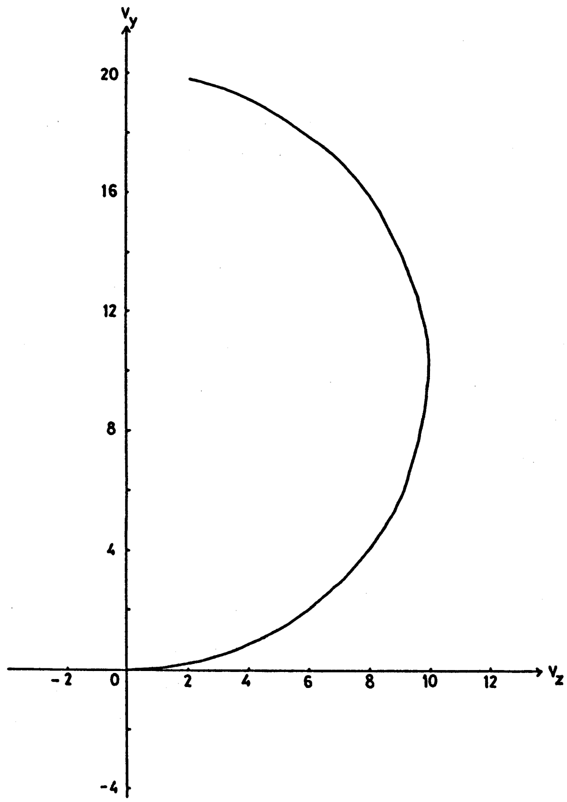

Fig. 4 Velocity-space orbit of a proton ($B_n/B_\infty=0.1$), $V_{ph}=1$, $V_{max}=15$, K=10, W=10. The proton initially trapped can be accelerated firstly to the Z direction and secondly to the Y direacion along the magnetic field. The detrapping does not occur in this stage.

takes place when the normal magnetic field B_n is small compared with the linear acceleration term W/K, i.e., $\varepsilon_n < W/K$.

Electrostatic Waves in the Neutral Sheet

We consider a theoretical possibility of the existance of the electrostatic waves near the tail neutral sheet. During the substorm activity, it is known that the plasma sheet becomes thinner and thinner to the order of proton Larmor radius (Nishida et al. 1976). This implies that the ion counter streams across the tail magnetic field is present. If the relative counter ion stream velocity across the magnetic field exceeds the proton thermal velocity, the modified two stream instability (MTSI) can be excited. The MTSI may generate the electrostatic waves propagating across the magnetic field with the frequency near the lower hybrid resonance one ω_{LH} and with a rapid growth rate, $\gamma_{max} \sim 0.1\ \omega_{LH}$. A computer simulation (Mcbride et al. 1972) shows that the saturation of the electrostatic waves can be estimated by the trapping in the wave potential. The saturated electrostatic field is given by

$$E_x = \frac{km}{4e}(U - V_{ph})^2, \qquad \cdots(8)$$

where k is the wave number of the wave, and U the proton counter stream velocity. By means of eq. (8) and k_{max} which gives the maximum growth rate of the MTSI, we can estimate the maximum velocity V_{max} as,

$$V_{max}/V_t = cE_x/V_t B_\infty \simeq (U/V_t)^2. \qquad \cdots(9)$$

In order to accelerate the protons up to ~Mev by the above mechanism, V_{max}/V_t must be about 10-30, or $U/V_t \simeq$ (3-6). The latter seems to be a reasonable value. These considerations make the presence of the electrostatic wave plausible.

The characteristic time scale τ_A of the acceleration is

$$\tau_A \simeq V_{max}/(V_{ph}\omega_C) = 2V_{max}/(U\omega_C) \qquad \cdots(10)$$

where we used $V_{ph} = U/2$ which corresponds to the maximum gnowth rate of the wave. By making use of eq. (9) we obtain $\tau_A = (2/\omega_c)(U/V_t)$, which is about 3-6sec. for $B_\infty \sim 20\gamma$ and very rapid. The electrostatic wave intensity E_x in (9) is required to be $E_x \simeq$ (50-100) mV/m, which is probably available when the magnetic reconnection takes place (Gurnett et al., 1976; Cattell and Mozer, 1982).

Conclusion

During the onset of substorm activity, high energy protons (up to Mev) can be rapidly accelerated by electrostatic waves. The presence of weak normal magnetic field leads to an effective proton acceleration along the magnetic field by a second step acceleration process.

Applications of this acceleration mechanism to the high energy (~Gev) proton production in the impulsive phase of solar flares will be published elsewhere (Sakai and Tajima, 1984).

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