NON-STOCHASTIC ACCELERATION OF PROTONS IN THE MAGNETIC NEUTRAL SHEET

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A rapid non-stochastic proton acceleration mechanism by electrostatic waves during the 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 process.

During a substorm activity, high energy protons (up to MeV) are observed in the distant tail[1]. Zeleny et al.[2] considered the proton acceleration in terms of 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.[3] observed electrostatic waves propagating almost perpendicular to the local magnetic field. Cattell and Mozer[4] also report that instantaneous field magnitudes rise up to 30mV/m when a substorm is active.

In this paper 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. This type of charged particle acceleration in a homogeneous plasma has been predicted by Sagdeev and Shapiro[5], and Sugihara and Midzuno[6]. Dawson et al.[7] proved the possibility by a computer simulation and Yoshizumi[8] et al. revealed the process experimentally.

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

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

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

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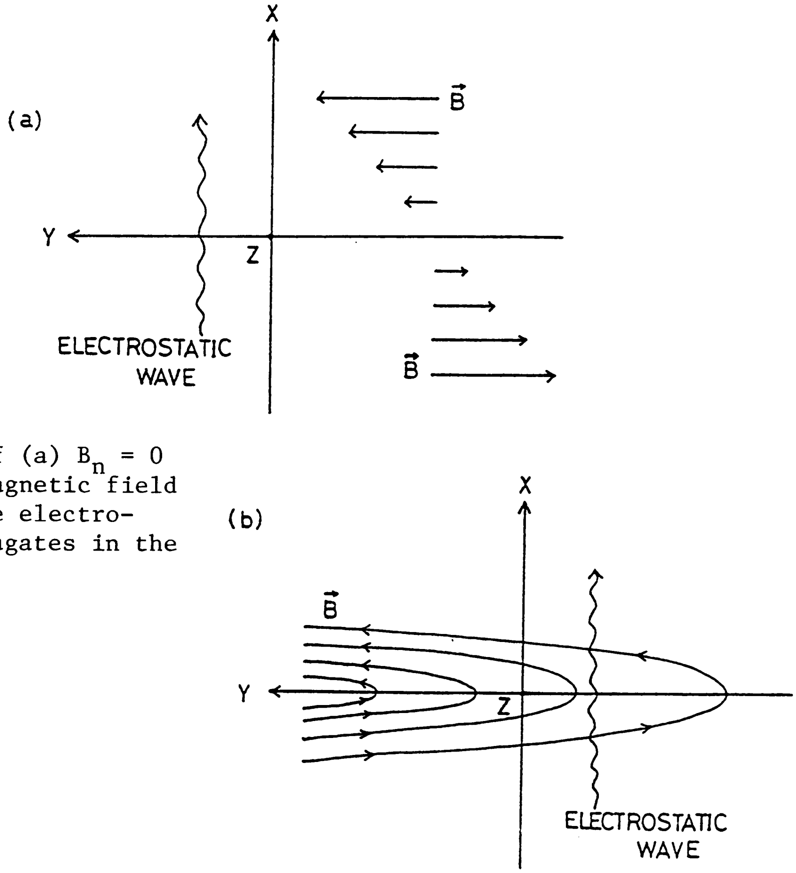

Fig. 1 Sketch of (a) $B_n = 0$ and (b) $B_n = 0$ magnetic field in the tail. The electrostatic wave propagates in the χ direction.

We assume that the driving wave is a lower hybrid one, has a form of $E_x \sin(kX - \omega t)$ and propagates across the current sheet in the positive X direction.

The equations of motion for a proton will be rewritten in the wave frame moving with the phase velocity. The non-dimensional forms are

$$\ddot{\xi} = \varepsilon \sin\xi - K\dot{Z} \tanh [(\xi + WT)/K] \, , \tag{2}$$

$$\ddot{Y} = \varepsilon_n \dot{Z} \, , \tag{3}$$

$$\ddot{Z} = K^{-1} (W + \dot{\xi}) \tanh [(\xi + WT)/K] - \varepsilon_n \dot{Y} \, , \tag{4}$$

where lengths, the time T and velocities are scaled with a, ω_c^{-1}, and the proton thermal velocity V_t, respectively, and $K = ka$, $W = \omega/\omega_c$, $\varepsilon = KV_{max}/V_t$, $V_{max} = cE_x/B_\infty$ and $\varepsilon_n = B_n/B_\infty$.

At first we examine the case of $\varepsilon_n = 0$. Suppose a proton initially trapped in a potential well of the wave and choose $\xi = 0$ at $T = 0$. From eq. (4), the proton is accelerated as it feels $\vec{V}_{ph} \times \vec{B}$(dc) electric field and the proton velocity in the X irection increases linearly with time. As time elapses the second term in the right hand side of eq. (2) becomes large and finally overcomes the electrostatic term, and then the proton detraps from the wave potential well. In Fig. 2 a typical example is shown for a proton which initial coordinates are X = Z = 0 and $V_z(0) = \dot{\xi}(0) = 0$. The parameters chosen are $\varepsilon = 150$, K = 10, W = 10, $V_{ph} = 1$.

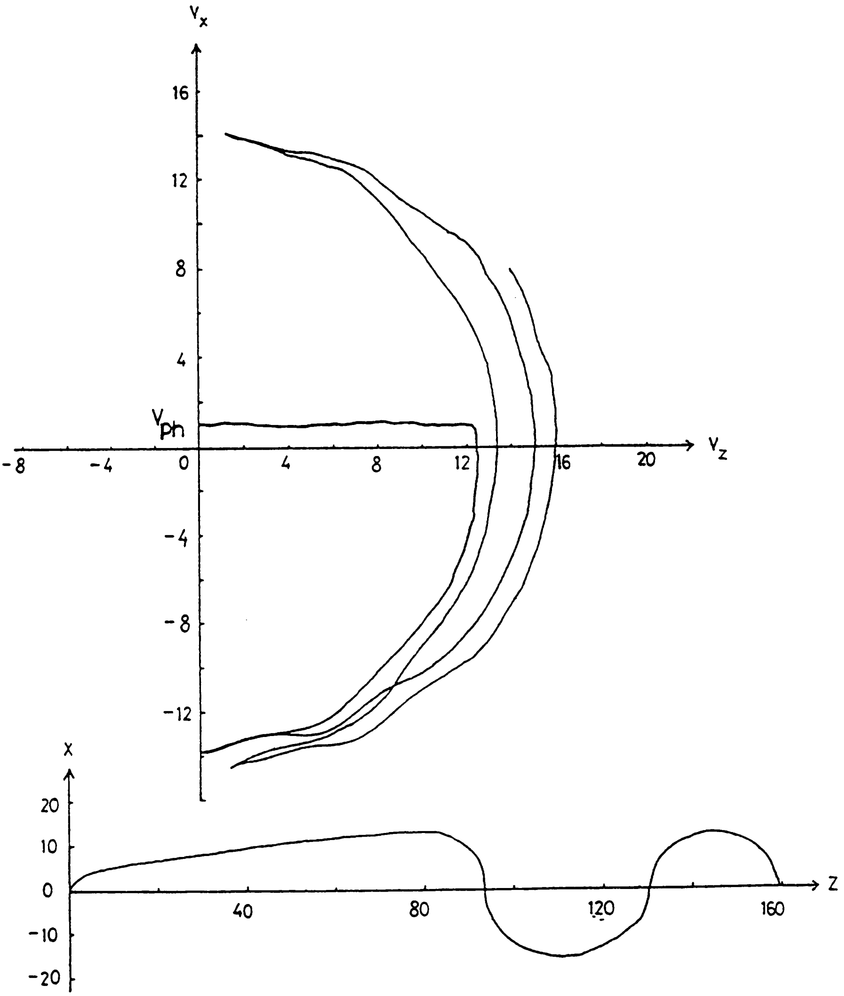

Fig. 2 Velocity-space orbit (upper) of a proton and orbit in the neutral sheet ($B_n = 0$). $V_{ph} = 1$, $V_{max} = 15$, K = 10, W = 10. The proton is initially trapped and $V_z(0) = 0$. After detrapping from the potential well, the proton moves crossing the neutral sheet.

The V_z at the point of detrapping is 12.4 which is a little bit smaller than $V_{max} = 15$ in the scale of V_t as shown in Fig. 2. Subsequently the acceleration time is a little shorter than the ideal τ_a. After detrapping, the proton moves crossing the neutral sheet or does the so-called meandering motion as shown in the lower portion of Fig. 2 and may be accelerated in the Z direction stochastically.

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 small, the linear acceleration in the Z direction can still occur as seen from eq. (4). Following this acceleration the particle is accelerated in the positive Y direction, which is seen from eq. (3). A theory[9] which treats the acceleration of a charged particle by a wave propagating obliquely to a homogeneous magnetic field predicts that $(V_z)_{max} = (\omega_c/\omega_{cn})V_{ph}$ and $(V_y)_{max} = 2(\omega_c/\omega_{cn})V_{ph}$ when the praticle does not detrap or $(V_z)_{max} <$ CE/B. This theory may be applicable to the present case because computed V_{max} and τ_a are very close to cE_x/B_∞ and $cE_x/(B_\infty\omega_c V_{ph})$. After the theory we expect that $(V_z)_{max} = 10$ and $(V_y)_{max} = 20$, which exactly agree with the computed results[10]. Then we anticipate that the maximum V_y is $2 \cdot V_{max} = 2\ CE/B_\infty$ which is twice larger than that in the case of perpendicular propagation of the wave.

During the substorm activity, it is known that the plasma sheet becomes thinner and thinner to the order of proton Larmor radius[11]. This implies that the ion counter streams across the tail magnetic field is present. Now we assume the presence of such streams. If the relative velocity U of the streams exceeds V_t, the modified two stream instability (MTSI) can be excited. The MTSI may generate electrostatic waves propagating across the magnetic field with frequencies near the lower hybrid resonance one ω_{LH} and with rapid growth rates, $\gamma_{max} \simeq 0.1\ \omega_{LH}$. A computer simulation[12] shows that the saturation of the electrostatic waves is estimated by the ion trapping in the wave potential. The saturated electrostatic field is given by

$$E_x = \frac{km}{4e}(U - V_{ph})^2 , \tag{5}$$

where k is the wave number of the wave. In explicity estimating E_x, instead of k we use $k_{max} = 17\omega_c/V_t$ which gives the maximum growth rate of the MTSI[13], and $V_{ph} = U/2$ which corresponds to k_{max}. Now V_{max}/V_t is given by

$$V_{max}/V_t = CE_x/(V_t B_\infty) \simeq (U/V_t)^2 \tag{6}$$

We estimate quantities required when protons are accelerated up to 0.5 MeV by the above-mentioned process. Suppose that the thermal energy of the proton be 1 keV and that the perpendicular acceleration be only responsible for this acceleration. Hence V_{max}/V_t must be 22 or $U/V_t \simeq 5$ from eq. (6). The latter seems to be a reasonable value. The intensity E_x is required to be 100 mV/m for $B_\infty = 10\gamma$. The time τ_a of the acceleration is

$$\tau_a = V_{max}/(\omega_c V_{ph}) = 2V_{max}/(\omega_c U) = (2/\omega_c)(U/V_t)$$

which is about 10 second.

Thus using a plausible assumption of the presence of the ion counter streams across the neutral sheet we semi-quantitatively interpret the existence of the electrostatic wave which produces results consistent with observed data.

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DISCUSSION

R. Smith: You showed single-particle trajectories in which the particle made many bounces before becoming untrapped. But if a wave saturates by ion trapping, there will be many trapped particles and sidebands will grow, detrapping the particle within just a few bounce periods. Thus there will be much less acceleration.

Sakai: I think that the growing time of sidebands may be very slow compared with the typical acceleration, time which is of the order of the proton gyro-period.

Huba: The ion-ion modified two stream instabilities are stable in high β systems such as the neutral sheet. They cannot provide electrostatic turbulence in the neutral sheet. It is very difficult for electrostatic turbulence to exist in the magnetotail neutral sheet - the turbulence is probably electromagnetic.

Sakai: The observation by Cattell and Mozer (1982) reports that the instantaneous electrostatic field amplitudes rise up to 30 mV/m when a substorm is active. During the dynamical thinning phase of neutral sheets, the ion-ion counter stream instability may create electrostatic waves.

D. Smith: Jim Eastwood calculated electron trajectories in neutral sheets (Planet. Space Sci. '73, '74). Have you compared your results with his?

Sakai: I think that Eastwood did not calculate the trajectory of a trapped proton by electrostatic waves in the neutral sheet, which is essential in this acceleration mechanism.