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Particle diffusion and adiabatic expansion of plasmoids

M S SINDHU, G RENUKA and C VENUGOPAL[†]

Department of Physics, University of Kerala, Kariavattom 695 581, India
[†]School of Pure and Applied Physics, M G University, Kottayam, India

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Abstract. In this paper neutral point (coalescence) instability (NPI) of plasmoids (PMD) associated with tailward streaming O^+, H^+ and e^- particles and diffusion region (spatial extent and particle life time) are studied. Also, radial and pitch angle diffusion studies have been carried out in the near-earth region (10 and 11 R_E) during substorm onset. Our study revealed that coalescence instability is favoured by a heavier ion like O^+ and the time required for a heavier ion to reach from one X point to an adjacent X point is minimum. Near an X type neutral line (diffusion region) ions spend a fairly long time and gain a significant amount of energy. Radial and pitch angle diffusion studies showed that higher energy particles are largely confined near the reconnection region (near-earth region) and lower energy particles are rapidly depleted from the near-earth region during substorm onset.

Keywords. Plasmoids; diffusion; neutral point instability.

1. Introduction

The process of magnetic reconnection and island (plasmoid) formation plays an essential role in energy dissipation in space plasmas. The plasma confinement in laboratory magnetic devices is similar to that in space plasma trapped configuration. Reconnection occurs in the diffusion region where particles can move nonadiabatically in the direction of the electric force to become accelerated. Biskamp and Schindler (1971) pointed out the fact that the current layer with periodic structure turns out to be unstable and leads the islands to coalesce.

Adjacent to the plasma sheet (PS), a boundary layer of tailward streaming energetic particles was observed before plasmoid entrance and after exit from the post plasmoid plasma sheet (Richardson R L *et al* 1989). The onset of intense streaming and counterstreaming directions was accompanied by excursions in the y component of the magnetic field which are expected at the trailing and leading edges of the closed magnetic loops (Kettman and Dally 1990).

Enhanced convection leads certain regions of the PS to become unstable which causes rapid local changes in the tail magnetic field (Pellinen 1993). In the earthward region injection of particles into the belt of trapped particles is observed in conjunction with the observation of plasmoids in the tail (Nishida 1990). Otto *et al* (1990) suggested that the entire or at least major part of the PMD is within the diffusion region.

We have studied the neutral point instability (coalescence instability) of plasmoids in presence of tailward streaming particles and the spatial extent and particle life time in the diffusion region. Particle diffusion near the reconnection region is also studied.

2. Materials and methods

The stability of two-dimensional collisionless plasmas in a sheet pinch with periodic structure has been considered by Biskamp and Schindler (1971). They evaluated the growth rate of neutral point instability, under the assumption that particles can oscillate between two neighbouring X points and those that can reach an adjacent X point and is given by

$$\gamma = kv_{\text{th}}d/l(\log l/d)^{-1/2} \tag{1}$$

$$\eta = \frac{1}{\left(\log\frac{l}{d}\right)} \tag{2}$$

where $k = 2\pi/\lambda$, λ being the longitudinal extent of the PMD, v_{th} the thermal velocity, and l is the plasma sheet extent. The fraction of the time the particle spends in the diffusion region η, the time taken by the particles to travel between two consecutive X type neutral points (τ_0) and particle energy W_j are found using the relations (2–4)

$$\tau_0 = \left[\frac{1}{kv_{\text{th}}\eta}\right] \tag{3}$$

$$W_j = W_{\text{th}j}\left[\frac{rl\gamma_j d_j}{\rho_j v_{\text{th}j}}\right]^2 \tag{4}$$

where $j = i, e$, and $r = 1$ if the instability changes the topology of the magnetic field and ρ_j is the particle gyroradius.

Within the diffusion region the orbit of a thermal particle consists of a rapid bounce motion between mirror points and an approximately straight line trajectory in the x direction. An X type neutral line is formed within the PS due to the tearing mode instability and the extent in z and x direction of the diffusion region (figure 1) respectively are given by (Coroniti 1985)

$$d_j = \frac{v_{\text{th}j}m_j c}{eB_x} \tag{5}$$

and

$$\Delta_j = \frac{v_{\text{th}j}m_j c}{eB_z} \tag{6}$$

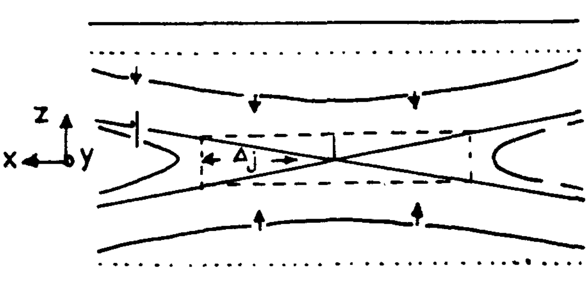


Figure 1. Schematic diagram of the diffusion region surrounding the neutral line (from Coroniti 1985).

respectively, where the parameters have the usual meaning. The length of the time the particle spends within the diffusion region is

$$\tau_j = \frac{2\Delta_j}{v_{\mathrm{th}j}}. \tag{7}$$

Particle will tend to be trapped in the O point (magnetic island) where the electric field is relatively weak (Ambrosiano *et al* 1988) and will not remain stably trapped in the neighbourhood of the X line.

At the onset of magnetospheric substorm, tail like field lines in the near-earth (~ 10 and 11 R_E) plasma sheet collapse rapidly to a dipole like field [Lewis *et al* (1990)]. During substorm at ~ 20–30 R_E a new neutral line (diffusion region) is formed due to reconnection. Reconnection region is typically 10 to 15 R_E from the X point to the earthward or tailward side. Since at 10 R_E the field lines are dipolar and the reconnection region extends over this distance we have studied the radial diffusion coefficient of electrons in the reconnection region.

For a substorm like electricfield A_E, the radial diffusion coefficient is given by (Cornwall 1968)

$$D_{LL} = 0{\cdot}25C^2 A_E^2 \left(\frac{L^3}{B_0}\right)^2 \left[\frac{T}{1 + 0{\cdot}5\omega_D T}\right]^2 \tag{8}$$

where

$$\omega_D = \left(\frac{3\mu c}{e^2 L^2 R_E^2}\right)\left(1 + \frac{2\mu B_0}{mc^2 L^3}\right)^{-1/2} \tag{9}$$

is the magnetic moment and other symbols have their usual meaning. Pitch angle diffusion is also a very efficient process in the magnetosphere, which quickly mixes particles mirroring at different points on a given field line. Fokker Planck equation can be used to study the effect of pitch angle diffusion on a population of electrons trapped in the magnetosphere, and is given by

$$D_{\alpha 0} = \frac{1}{3}\left(\frac{e}{mc}\right)^2 B_{(fo)} \tag{10}$$

where $B_{(fo)}$ is the power spectral density of one magnetic field component of waves evaluated at resonant frequency fo and hence life time $T(=1/D_{\alpha 0})$ of electrons.

Within the diffusion region perpendicular field component becomes progressively smaller as the X line is approached while parallel field increases with distance from the diffusion region.

3. Results and discussion

3.1 *Neutral point instability (NPI) and diffusion region*

Adjacent to PMD boundary layer, tailward streaming particles are observed and we have considered O^+, H^+ and e^- as tailward streaming particles. Since it is streaming tailward it passes between two X points and with that assumption we have studied the NPI of PMDs in presence of tailward streaming particles.

In the present study we have chosen PMDs reported in Richardson, I G *et al* (1989). The numerical values used in the present study are

1. Longitudinal extent of the plasmoid = 35, 40, 60, 80 and 95 R_E.
2. Temperature = 240, 260, 310, 290 and 120 eV and
3. Magnetic field strength = 22, 23, 8, 8 and 8 nT.

Using equations (1–4) we have obtained the growth rate γ of O^+, H^+ and e^-, life time at which the particle spends within the diffusion region η, time at which particles travel between two consecutive X points τ_0 and particle energy.

Figure 2a shows the growth rate of O^+ (solid line), H^+ (dashed line) and e^- (dotted line) vs the longitudinal extent λ of plasmoids. For O^+ and H^+, γ decreases from 35 to 40 R_E and has maximum at 60 R_E and minimum at 95 R_E. But for e^-, γ is maximum at 80 R_E and minimum at 95 R_E.

Maximum growth rate at 60 R_E is due to its relatively high temperature (310 eV). Growth rate is found to decrease with the increase in λ which is in analogy with Richardson R L *et al* (1989) that small islands coalesce to form large magnetic islands which move down the tail. Growth time is minimum for O^+ (1·2–3·9 min) and is maximum for H^+ (2167·03–10046·2 min). This shows that coalescence instability is favoured by massive ions like O^+.

Figure 2b shows the life time at which O^+, H^+ and e^- spends in the diffusion region η vs λ. It is clear from figure 2b that the variation in η is uniform for O^+, H^+ and e^-. η is nearly constant at 35 to 40 R_E and increases to a maximum at 60 R_E and then decreases. η is maximum for O^+ (0·424–0·434 sec) and is minimum for H^+ (0·373–0·362 sec).

Figure 2c shows the time at which the particle travels between two consecutive X type neutral points τ_0 vs λ. τ_0 is found to increase with the increase in λ. However, O^+ requires a minimum time (0·4943–1·8422 sec), while H^+ takes a fairly long time (443·81–1751·83 sec) to reach the adjacent X point which shows that O^+ will stream faster than H^+ and e^-. Tailward streaming particles is a signature in identifying a PMD region and from the result it is obvious that O^+ will stream ahead of a plasmoid and can be detected prior to lighter ions.

Figure 2d shows the variation of particle energy vs λ. O^+ is found to gain a significant amount of energy (4·59–26·34 keV) than H^+ (0·9–27·8 eV) and e^- (0·46–2·6 keV).

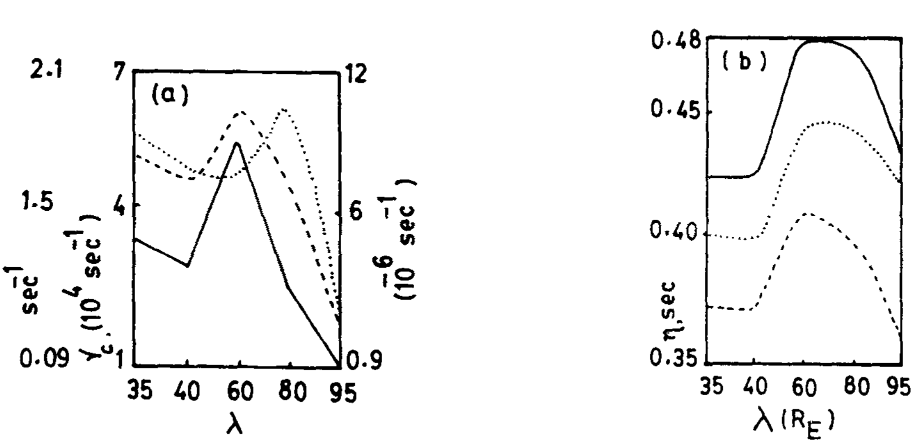
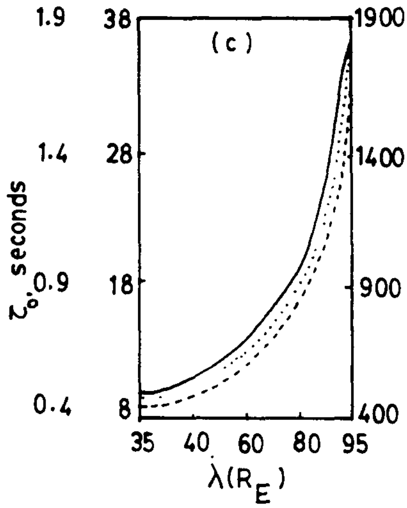


Figure 2a and b



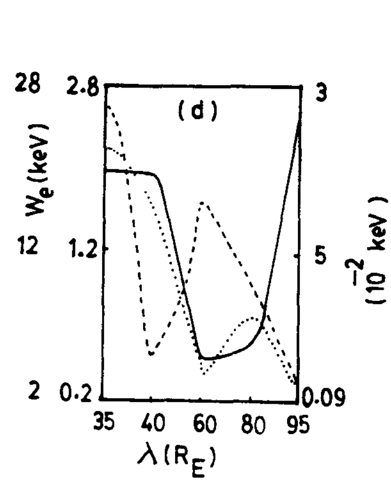


Figure 2c and d.

Figure 2a–d. Variation of (**a**) γ (**b**) η (**c**) τ_0 and (**d**) W_e with longitudinal extent of the plasmoid for O^+ (—), H^+ (– –) and e^- (. . .) streaming particles.

In table 1 the spatial extent (both in z and x direction) and the time at which the thermal particle spends within the diffusion region are given. It revealed that as the magnetic field increases the spatial extent of the diffusion region decreases, which in turn is well reflected on the time at which the particle spends in the diffusion region.

For a thin sheet the particle spends a relatively large amount of time in the region where it dominates and can gain a significant amount of energy. The thickness of the diffusion region is $\sim 0{\cdot}1\ R_E$ and the life time of protons in the diffusion region is 31·31–41·76 sec whereas electron life time is only 0·0173–0·0227 sec. Thus it can be concluded that higher energy particles are largely confined near an X type neutral line.

This is in analogy with Scholer and Jamitzky (1989) that protons were accelerated near the X line to 1–200 keV depending on how close they reached the neutral line after injection. The energy gained by ions is found to be greater than that of electrons. The particle acceleration in the neutral sheet or near a neutral line takes place because low energy particles are not impeded by the small magnetic field in the vicinity of the

Table 1. The spatial extent and the time the particle spends in the diffusion region.

B_x nT	d_p km	d_e km	B_z nT	Δ_p km	Δ_e km	T_p sec	T_e sec
0·5	1595·16	187·65	0·15	8480	62·69	41·76	0·0227
1	1272·27	93·82	0·16	7950	58·77	39·14	0·0213
1·5	848·18	62·55	0·17	7482	55·32	36·84	0·0200
2	636·14	46·91	0·18	7066	52·24	34·79	0·0189
2·5	508·91	37·53	0·19	6694	49·49	32·96	0·0179
3	424·09	31·27	0·20	6360	47·00	31·31	0·0173

neutral sheet from being associated by the cross tail electric field. This process is much more effective for ions than electrons because particles tend to gain a velocity increase independent of their mass. Kettman and Dally (1990) suggested that the neutral lines are expected to be the source of energetic ion and electron beams that can be observed in the vicinity of the most recently reconnected field lines. In general these results are in

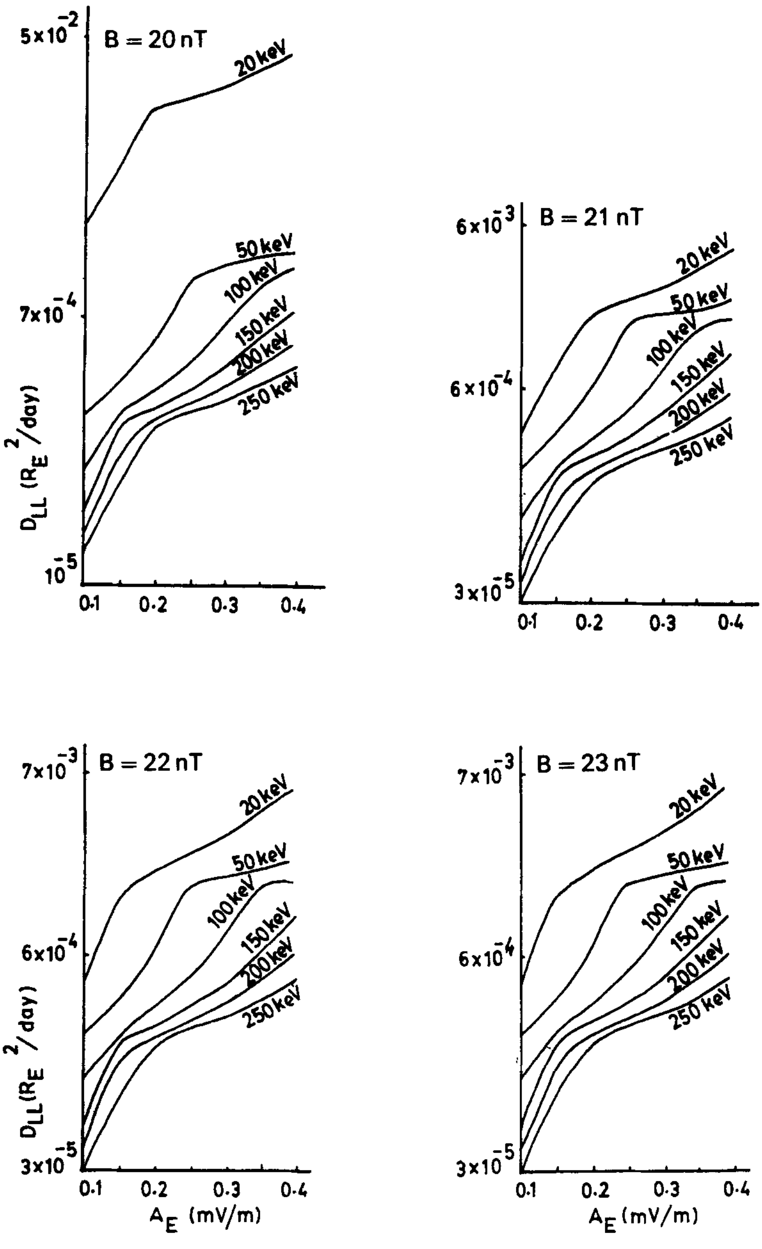


Figure 3a.

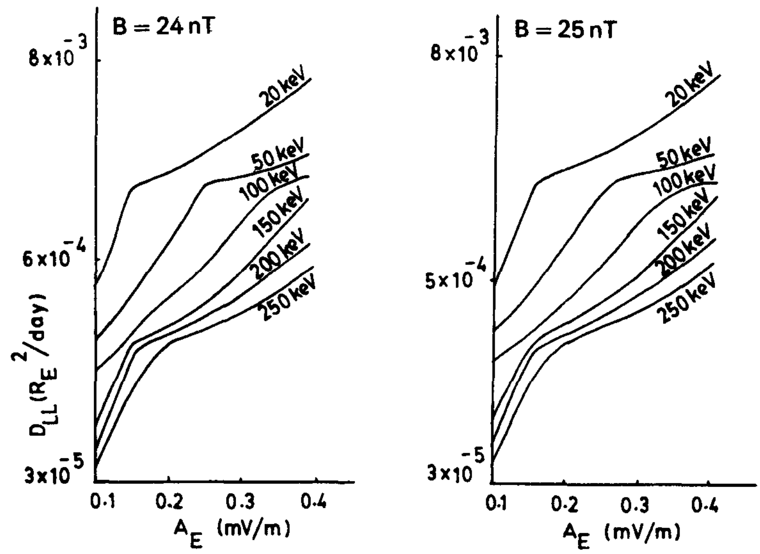


Figure 3a.

agreement with Martin (1986) that the energy gained by a singly charged ion while passing through the acceleration region depends on the sheet thickness, the initial energy, initial pitch angle, initial X position and particle mass.

3.2 *Adiabatic expansion of plasmoids*

Even though the plasma confined in a magnetic island may tend to expand, the surrounding antiparallel magnetic field will prevent the plasma from expanding away. It is discussed in section 3.1 that as the longitudinal extent of the plasmoid increases the particle energy decreases while Renuka *et al* (1992) suggested that as λ increases the total energy content in a PMD increases. Since the energy content increases the plasma confined in the island overcome the force exerted by the surrounding magnetic field and tend to expand. Hence we can suggest that plasmoids expand adiabatically as it moves into a weaker tail field. Sibeck (1990) concluded that plasmoids grow as they propagate down the tail. While Moldwin and Hughes (1992) found that PMDs change very little as they move down the tail, they argued that the size, velocity, magnetic core strength and B_z field amplitude of PMDs do not depend on the distance beyond 100 R_E downtail.

The interaction between the plasma confined in the island and the surrounding magnetic field causes an oscillation in the system (Ugai 1981). The amplitude of oscillation should become larger as the amount of plasma energy confined in the magnetic island becomes larger since the confined plasma pressure gives the expansion force. Since the energy content in a PMD is found to be large for large PMD the amplitude of oscillation is relatively large for larger islands and its period is approximately given by the time required for a fast wave to travel one periodic distance in the X direction.

3.3 *Particle diffusion*

Using equations 8 and 10 the radial diffusion coefficient D_{LL} and pitch angle diffusion coefficient $D_{\alpha o}$ of trapped electrons can be studied. The numerical values of the parameters used are

Electron energy (E_e) = 20, 50, 100, 150, 200 and 250 keV.
Electric field amplitude $\langle A_E \rangle$ = 0·1–0·4 mV/m.
Period (T) = 1 hour.

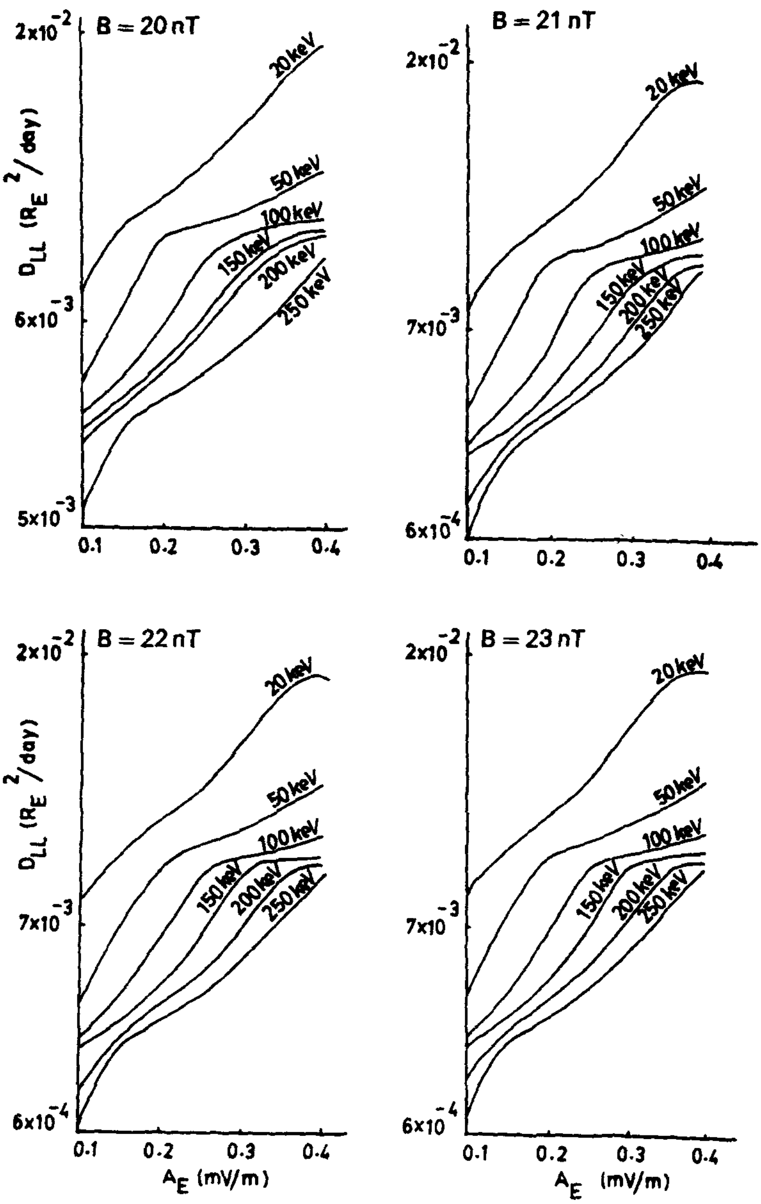


Figure 3b.

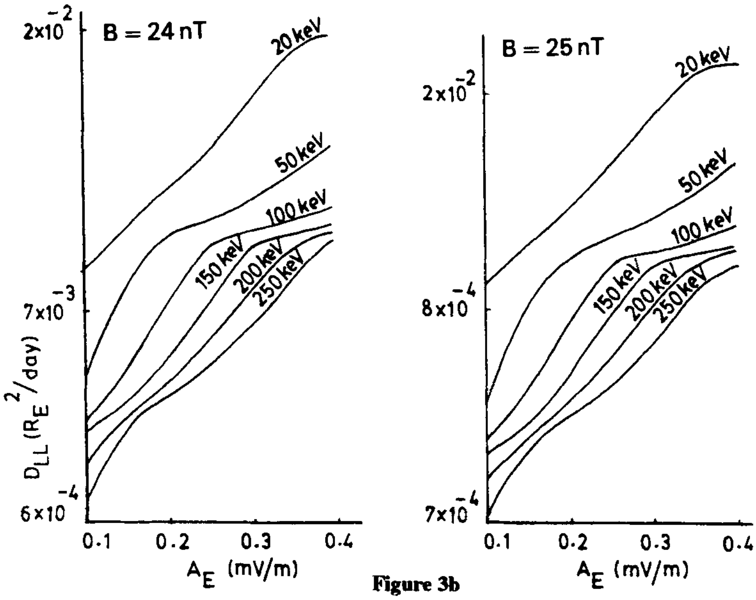


Figure 3a and b. Variations of radial diffusion coefficient D_{LL} with electric field A_E for different magnetic field B and (a) at $L = 10$ (b) at $L = 11$.

D_{LL} is plotted against A_E for electron energies of 20, 50, 100, 150, 200 and 250 keV at $L = 10$ and 11 (figures 3a and 3b). D_{LL} is found to increase with the increase in A_E. As electron energy increases D_{LL} decreases. When L increases from 10 to 11, D_{LL} increases. As an example, at $L = 10$, for $E_e = 20$ keV, $B = 21$ nT and $A_E = 0{\cdot}4$ mv/m, D_{LL} is $5{\cdot}2704 \times 10^{-3}$ R_E^2/day. When $L = 11$, D_{LL} increases to $1{\cdot}22 \times 10^{-2}$ R_E^2/day, variation in D_{LL} frequently occurs for $A_E \geqslant {\cdot}15$ mV/m for $L = 10$, while for $L = 11$, D_{LL} variation occurs at $A_E \geqslant 0{\cdot}2$ mV/m. However, for $E_e = 250$ keV, D_{LL} varies at $A_E = 0{\cdot}15$ mV/m. A small variation in D_{LL} can be seen for $L = 10$ and 11 at energies > 100 keV. This shows that higher energy particles are largely confined near the reconnection region and the low energy particles are rapidly depleted from the reconnection region. Hence we can confirm that tailward moving PMDs carry with it only low energy particles.

Figure 4 shows the plot of pitch angle diffusion coefficient vs magnetic field. It is clear from this figure that the effect of magnetic field is negligible to the pitch angle diffusion coefficient. However a relatively small variation can be seen for $E_e < 100$ keV. Life time of electrons having energies > 100 keV shows a large variation.

4. Conclusion

The heavier particles were first detected in the identification of plasmoids using tailward streaming particles. For thin sheet particles spend a fairly long time and higher energy particles are largely confined near an X type neutral point. Coalescence instability of plasmoids is favoured by heavier ions and minimum time is required for heavier ions to reach from one X point to the adjacent X point. Radial and pitch

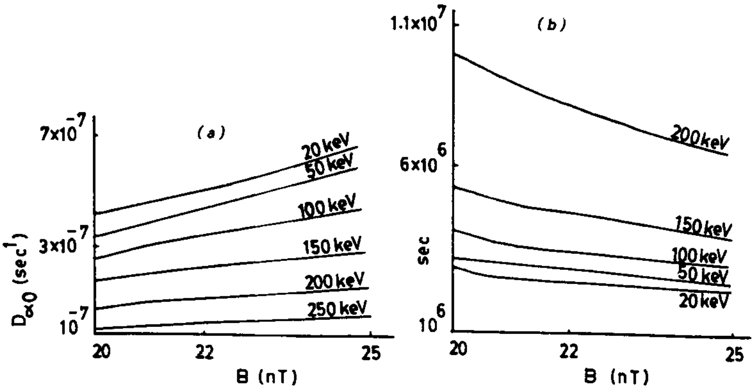


Figure 4. Variation of (**a**) pitch angle diffusion coefficient $D_{\alpha 0}$ and (**b**) electron life time, with magnetic field B.

angle diffusion studies showed that higher energy particles are largely confined near the reconnection region (near-earth region) and the low energy particles are rapidly depleted from the near-earth region during substorm onset.

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References

Ambrosiano J, Matthaesus W H, Goldstein M L and Plante D 1988 Test particle acceleration inturbulent reconnecting magnetic fields; *J. Geophys. Res.* **93** 14353

Biskamp D and Schindler K 1971 Instability of two dimensional collisionless plasmas with neutral points; *Plasma Phys.* **13** 1013

Cornwall J M 1968 Diffusion processes influenced by conjugate point wave phenomena; *Radio Sci.* **3** 740

Coroniti F V 1985 Explosive tail reconnection: The growth and expansion phase of magnetospheric substorms; *J. Geophys. Res.* **85** 6719

Kettman G and Dally P W 1990 Energetic ion flow reversals on ISEE 1 and 2: Indications for substorm neutral lines; *Ann. Geophys.* **8** 115

Lewis Z V, Cowley S W H and Southwood D J 1990 Impulsive energization of ions in the near-earth magneto-tail during substorms; *Planet Space Sci.* **38** 491

Martin R F 1986 *Ion acceleration in the magnetosphere and Ionosphere* (ed.) Tom Chang, (Washington DC: AGU) 141

Moldwin M B and Hughes W J 1992 On the formation and evolution of plasmoids: A survey of ISEE 3 geotail data; *J. Geophys. Res.* **97** 19259

Nishida A 1990 Magnetic reconnection in the tail of the magnetosphere; *Adv. Space Res.* **10** 135

Otto A, Schindler K and Birn J 1990 Quantitative study of nonlinear formation and acceleration of plasmoids in the Earth's magnetotail; *J. Geophys. Res.* **95** 15023

Pellinen R 1993 How does magnetospheric convection relate to the expansion onset of substorms?; *J. Atmos. Terr. Phys.* **55** 1137

Renuka G, Sindhu M S and Venugopal C 1992 Plasma β parameter dependence on plasmoids; *Indian J. Phys.* **B66** 339

Richardson I G, Owen C J, Cowley S W H, Galvin A B, Sanderson T R, Scholer M, Slavin J A and Zwickl R D 1989 ISEE 3 observations during the CDAW 8 intervals. Case studies of the distant geomagnetic tail covering a wide range of geomagnetic activity; *J. Geophys. Res.* **94** 15189

Richardson R L, Walker R J, Sydera R D and Abdulla M A 1989 The coalesence of magnetic flux ropes and reconnection in the magnetotail; *J. Geophys. Res.* **94** 2471

Scholer M and Jamitzky F 1989 Plasmoid associated energetic ion bursts in the deep magnetotail: Numerical modelling of the boundary layer; *J. Geophys. Res.* **94** 2459

Sibeck D G 1990 *Evidence for flux ropes in the earth's magnetotail in Physics of magnetic flux ropes* (ed.) C T Russell (Washington: AGU)

Ugai M 1981 Nonlinear development of magnetic reconnection in tearing type and the Petschek type field geometries; *Plasma Phys.* **23** 857