# Chapter 4

**Non-adiabatic Behaviour of the Substorm-time Near Earth Plasma Sheet**

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4.1 Introduction

Magnetic reconnection and the occurrence of magnetic substorms play an important role in building up the dynamics of the plasma sheet. Numerous statistical studies using plasma measurements made by different satellites have contributed to a considerable progress in our understanding of this plasma domain. The study of the heating and convection mechanisms in PS happens to be the key problem in exploring its adiabatic behaviour.

The Near Earth Plasma Sheet (NEPS) is a region well covered by satellite observations. Various case studies using these observations have been done and their results helped a lot in explaining the behaviour of the NEPS. For example, the thinning and the subsequent thickening of PS during magnetospheric substorms were observed at distances from around $15\ R_E$ covered by VELA and ISEE satellites, up to at least $35\ R_E$ down the tail by IMP satellites (Slavin et al. 1985). The non-adiabatic heating processes of the central NEPS up to the perigee ($23\ R_E$) of ISEE 1 satellite were examined by Huang et al. (1992) and the plasma and magnetic field parameters at substorm onsets at GEOS 2 site were analyzed by Pu et al. (1992). Non-adiabatic acceleration of ions in the geomagnetotail was studied by Frank et al. (1994). The magnetic connectivity between the auroral region of the ionosphere and the equatorial geosynchronous region of magnetosphere were also studied using the plasma measurements made by the DMSP satellite (Hones et al. 1996).

A magnetospheric substorm has a major influence on the central NEPS. The ion temperature of PS was observed to increase to a value twice that at the pre-substorm period during the expansion phase of a substorm (Baumjohann,
1991). But in the boundary layer of NEPS, the ion heating processes are intense during its recovery phase. The substorm-time temperature of NEPS at the site of GEOS-2 observations was computed by Bindu et al. (1996). The thermal and electrical conductivities of NEPS during substorm onset times were calculated and their dependence on various solar and PS parameters were studied (Prince et al. 1997a & b; See chapter 2 and 3 also).

The analysis carried out by Huang et al. (1992) suggested that the substorm time heating mechanisms in NEPS, closer to earth, is adiabatic, but is not so beyond 10 $R_E$. In this Chapter, the behaviour of NEPS during the selected substorm onsets (Table 2.1) is dealt with. The study is carried out for the geosynchronous PS at 6.6 $R_E$ and the result shows that NEPS behaves non-adiabatically at the site at least at the onset times of substorms (Sec.4.3 and 4.4). These deviations from the earlier findings (Huang et al. 1992) and its cause have been addressed. Also a full course of substorm (Sec. 4.5) is analysed and found that the heat exchanges are non-adiabatic at 13-15 $R_E$ during substorm expansion and recovery phases. But the heat transactions were shown to be adiabatic during the growth phase.

4.2. Equation of state and polytropic index

The thermodynamic equation of state for space plasma representing heat transactions as proposed by Siscoe (1983) is

$$P = \alpha N^\eta$$  \hspace{1cm} (4.1)
where \( P \) is the plasma thermal pressure, \( N \) the plasma number density, \( \eta \) the polytropic index and \( \alpha \) is a constant, which depends on the specific entropy of plasma. The quantity \( \eta \) expresses how much the temperature \( T \) of plasma increases as it is compressed since, \( PV^{\eta} = \) constant, (or \( TV^{\eta-1} = \) constant) where \( V \) is the plasma volume. As such, the equation of state constitutes a simple statement about the heat flow. \( \eta \) ranges from 0 (isobaric plasma) to \( \infty \) (isometric plasma with constant density). For the case of compression that is slow compared to thermal conduction, \( \eta = 1 \), which represents isothermal compression. Or, the pressure goes up only because the density goes up. In many cases, because particles can stream along a magnetic field \( B \), conduction parallel to \( B \) provides an avenue for plasma to remain isothermal, if the compression is, for example, periodic or wavelike along \( B \) (Goldston and Rutherford, 1995).

On the other hand, if the compression is fast enough (faster than heat conduction) so that the transitions are adiabatic, but slow enough that the energy is exchanged between the three degrees of freedom \((f = 3, \) assuming PS particles to be fairly isotropic) through collisions, \( \eta = (f+2)/f = 5/3 \). The fact that the space plasma can support a number of different types of waves, some of which compress the plasma isothermally, while others compress it adiabatically, has a significant effect on the plasma wave dynamics.

There were many efforts in the literature to find out an acceptable equation of state for PS. Siscoe's (1983) adiabatic equation

\[
P = \alpha N^{5/3}
\]

(4.2)
was the one proposed first. Since this relation is actually the solution of the energy equation when the plasma is experiencing an adiabatic compression, it characterizes the energy transport in plasma. Baumjohann and Paschmann (1989) have shown that Eqn. 4.2 is in excellent agreement with PS conditions especially in active periods (\(AE > 100\ \text{nT})

Kan and Baumjohann (1990) have shown that only the compression in the distant PS or the PSBL (> 20 \(R_E\)) can be expected to follow the standard adiabatic equation of state (Eqn. 4.2). They put forward another equation of state for compressions in the CPS (< 20 \(R_E\)), which was derived from the invariance of the magnetic moment under the assumption of isotropic pressure. This equation known as the isotropized magnetic moment equation is

\[
\frac{P}{NB} = \text{a constant} \quad (4.3)
\]

where \(B\) is the normal field component in PS. The equation was deduced based on Tsyganenko magnetic field model. Its deduction incorporates calculation of radial profile of the plasma pressure near the neutral sheet under the assumption of pressure equilibrium between the magnetic pressure in the lobe and the thermal pressure near the neutral sheet.

But the plasma density and pressure measured by AMPTE/IRM satellites in PS under quiet conditions fall in between the predictions of adiabatic equation of state (Eqn. 4.2) and the isotropized magnetic moment equation of state (Eqn. 4.3) (Baumjohann, 1993). A hybrid equation of state
(Kan et al. 1992) derived from a simple combination of Eqns. 4.2 and 4.3 was shown to be in excellent agreement with AMPTE/IRM method. The hybrid equation is

$$p^{2+\varepsilon} B^{2(\varepsilon-1)} N^{-(2+3\varepsilon)} = K_m$$  \hspace{1cm} (4.4)

where $K_m$ is a constant and the parameter $\varepsilon$ ranges from 0 to 1. If $\varepsilon = 1$, the adiabatic Eqn. 4.2 is resulted and if $\varepsilon = 0$, the isotropized magnetic moment Eqn. 4.3 is recovered. The density and temperature predicted by the hybrid equation of state with $\varepsilon = 0.15$ were in good agreement with the AMPTE/IRM data for quiet PS. The value of $\varepsilon$ can be expected to increase with increased disturbance in PS.

4.3. NEPS at Geosynchronous orbit

Twenty-two substorm onsets (Table 2.1) occurred in the midnight sector was selected. The behaviour of the NEPS at 6.6 $R_E$ was analysed using different parameters characteristic of these events. Since the thermal energy of ions is much greater than that of electrons in PS, we need only to consider the ion pressure ($P_i$) and density ($N_i$) for the equation of the state. Also the electron density was proved to be rather unaffected than the ion density during substorms and onsets (Pu et al. 1992). Hence, Eqns. 4.1- 4.4 can be rewritten as
\[ P_i = \alpha N_i^\eta \]  \hspace{1cm} (4.5)

\[ P_i = \alpha N_i^{5/3} \]  \hspace{1cm} (4.6)

\[ \frac{P_i}{N_i B} = \text{a constant} \]  \hspace{1cm} (4.7)

\[ P_i^{2+\varepsilon} B_i^{2(\varepsilon-1)} N_i^{-(2+3\varepsilon)} = K_m \]  \hspace{1cm} (4.8)

The polytropic index \( \eta \) can be obtained from the slope of \( \log P_i - \log N_i \) graph and it helps in determining whether the NEPS is adiabatic or not.

Since \( \eta \) obtained does not suit for an adiabatic geosynchronous PS at onsets (Sec. 4.4), the value of \( \varepsilon \), for which the hybrid Eqn. 4.8 is satisfied, is found out further. It is to be noted that \( \varepsilon \) further clarifies whether an adiabatic equation of state or the magnetic moment equation of state fits well into the situation; \( \varepsilon = 0 \) for constant magnetic moment equation and \( \varepsilon = 1 \) for adiabatic equation. For this analysis, a statistical approach is employed, in which the \( K_m \) (Eqn. 4.8) for all the 22 onsets have been calculated for \( \varepsilon = 0 \) to \( \varepsilon = 1 \) in steps of 0.1. The constancy of \( K_m \) for different onsets for a particular \( \varepsilon \) was checked by finding the nature of variations of \( K_{p,d} \), the percentage deviation from the mean of \( K_m \)'s. The \( \varepsilon \) value for which the \( K_{p,d} \) is smallest is accepted as the most suitable value for Eqn. 4.8. The percentage mean deviation (p.m.d) is also taken into account in deciding the acceptable value of \( \varepsilon \).
4.4. Results and discussion

4.4.1 Evaluation of polytropic index

A statistical evaluation of $\eta$ can be done by plotting log $P_i$ vs. log $N_i$ for the selected 22 events as in Fig. 4.1. The regression line is also shown. A fairly good correlation with a correlation coefficient $r = 0.9285$ is obtained. The slope of the line gives $\eta$ as per Eqn. 4.5. The value of $\eta$ obtained was 1.041 which is well below 5/3 (= 1.67), the critical value for transactions to be adiabatic. Thus it seems PS at the geosynchronous distance is a little bit non-adiabatic during substorm onsets. Even with an obtained value of $\eta \approx 1$, one cannot propose the existence of an isothermal geosynchronous PS, as there are little chances for temperature remaining constant at substorm onsets. In order to determine whether a non-adiabatic heating or a cooling occurs at the onsets, one has to take care of temporal variations of the specific entropy parameter $\alpha$ too. Therefore, one can assume the existence of an imbalance (i.e., non-adiabaticity) between the heating and energy dissipation levels in NEPS. Hence apart from polytropic index, a better understanding of the selected events is required to predict the thermal properties of NEPS. So, a further analysis for the adiabatic/non-adiabatic nature is performed using hybrid equation of state. One can also check for the constancy of the isotropized magnetic moment equation. But since the $\varepsilon$ parameter of the hybrid equation checks the validity of Eqn. 4.7 too, such an analysis is not done.
Fig. 4.1 - log $P_i$ vs. log $N_i$ for the 22 onsets
4.4.2. Equation of state for the NEPS at geosynchronous orbit

The constancy of Eqn. 4.8 for arbitrary $\varepsilon = 0, 0.1, 0.2, \ldots 0.8, 0.9$ and 1 have been checked. The parameter $K_{p,d}$ is taken as a measure of the steady nature of $K_m$. The smaller the degree of variations in $K_{p,d}$ the steadier the $K_m$ is.

The variation of $K_{p,d}$ was found to be smallest for $\varepsilon = 0.3$. This is evident from Figs. 4.2.a - j, in which $K_{p,d}$ vs. substorm events for different $\varepsilon$'s were compared with that for $\varepsilon = 0.3$. The p.m.d obtained for $\varepsilon = 0.3$ was 26.13, which is smaller than those obtained for all other $\varepsilon$. The p.m.d's for different $\varepsilon$'s are also shown if Figs. 4.2.a - j. The most appropriate value of $\varepsilon$ is 0.3 and is well in agreement with that given by Kan and Baumjohann (1990). Since 0.3 is closer to 0 (magnetic moment equation) than to 1 (adiabatic equation), it can be suggested that, in describing NEPS at geosynchronous orbit, the stronger magnetic fields become increasingly important. And the existence of a non-adiabatic NEPS at the geosynchronous orbit can be proposed. The result is contradictory with that obtained by Huang et al. (1992) based on ISEE observations, according to which a major difference between substorm processes that occur at 10-23 $R_E$ and those at geosynchronous distances lies in the mechanisms which is non-adiabatic beyond 10 $R_E$, but may be adiabatic closer to earth. The analysis carried out in this Chapter reveals that the mechanism is non-adiabatic at least at 6.6 $R_E$, the GEOS 2 orbit at substorm onsets.

The reason for this non-adiabatic nature can be the imbalance between the heating due to the plasma injection and the cooling due to particle losses.
Fig. 4.2.a $K_{pd}$ for different onsets

Fig. 4.2.b $K_{pd'}$ for different onsets

p.m.d. ($\epsilon = 0$) = 29.80
p.m.d. ($\epsilon = 0.3$) = 26.13

Onsets: $\square \epsilon = 0 \quad \Box \epsilon = 0.3$

Onsets: $\square \epsilon = 0.1 \quad \Box \epsilon = 0.3$
Fig. 4.2.c $K_{p,d}$ for different onsets

Fig. 4.2.d $K_{p,d}$ for different onsets
Fig. 4.2.e $K_{p,d}$ for different onsets

Onsets

| $\varepsilon = 0.5$ | $\varepsilon = 0.3$ |

p.m.d. ($\varepsilon = 0.5$) = 28.32
p.m.d. ($\varepsilon = 0.3$) = 26.13

Fig. 4.2.f $K_{p,d}$ for different onsets

Onsets

| $\varepsilon = 0.6$ | $\varepsilon = 0.3$ |

p.m.d. ($\varepsilon = 0.6$) = 31.63
p.m.d. ($\varepsilon = 0.3$) = 26.13
Fig. 4.2.g $K_{p,d}$ for different onsets

Fig. 4.2.h $K_{p,d}$ for different onsets
p.m.d. ($\varepsilon = 0.9$) = 43.67
p.m.d. ($\varepsilon = 0.3$) = 26.13

$p.m.d. (\varepsilon = 1) = 47.42$
$p.m.d. (\varepsilon = 0.3) = 26.13$

Fig. 4.2.i $K_{p.d.}$ for different onsets

Fig. 4.2.j $K_{p.d.}$ for different onsets
into the ionosphere or heat transport away from the sheet by various electrostatic or electromagnetic waves. The concept of plasma injections can be formulated through two approaches – one based on the Near Earth Neutral Line (NENL) model (Sec. 1.9.5) and the other based on the $E \times B$ drift.

As per the NENL model, at some time during the late growth phase of a substorm, the vertical component of the magnetic field across PS becomes sufficiently small that ions in the cross-tail current begin to behave non-adiabatically. Coroniti (1985) and Baker and McPherron (1990) suggest that at that point the magnetic reconnection begins in NENL. The flow of particles both tailward and earthward is thus triggered. The accelerated particles moving earthward from the reconnection site carry energy and are responsible for the non-adiabaticity of the geosynchronous PS. Finding the NEPS to be non-adiabatic at geosynchronous orbit implies that the NENL can be very close to the earth and the particles can reach even to an altitude of 6.6 $R_E$.

The other approach takes care of the formation of the induced electric field during the process of collapse of magnetic field lines from tail-like to dipolar form during onsets (Delcourt et al. 1990). This enhancement in the electric field enhances the $E \times B$ drift speeds too. The drift speeds thus achieved can be considerable and the resultant plasma yields transient non-adiabatic behaviour at geosynchronous distances.

Another possibility for this non-adiabatic nature can be the non-adiabatic motion in the cross-tail current sheet (Sec. 1.7.2) (Lyons and Speiser, 1982). During growth phase of substorms, the cross-tail electric field is increased, which in turn enhances particle energization. But this increase in
energy is rather kinetic than thermal. In order that this kinetic energy to contribute for the non-adiabaticity, it has to be transformed into thermal energy. This transformation from kinetic plasma into thermal plasma requires some scattering mechanisms at the geosynchronous distances and any such mechanism is yet to be detected.

The mechanisms of cooling or dissipation of heat has been well addressed in Chapters 2 & 3. So, it can be noted that these heating and cooling events and a resultant imbalance between the two causes a non-adiabatic nature for the geosynchronous PS at substorm onsets.

4.5 Adiabatic/non-adiabatic behaviour of PS during single substorm

The 22 March 1979 substorm considered in Chapters 3 & 4 is analysed for adiabatic/non-adiabatic behaviour. The signatures of the events as measured in the NEPS by the ISEE 2 satellite in the magnetotail are utilized. During the above substorm interval, ISEE 2 was at ~13-15 $R_E$ down tail (Paschmann et al. 1985). The study brings out new results of thermodynamic interest.

The plasma ion pressure $P_i$ and ion density $N_i$ during the full course of the substorm as measured by ISEE 2 are shown in Figs. 4.3 and 4.4 respectively. The $z$ component of the tail magnetic field measured by the same satellite is depicted in Fig. 4.5. The particular substorm has a growth phase with a duration of ~ 35 minutes starting at 1020 UT. The expansion phase onset begins at 1055 UT and the phase lasts for ~45 minutes. At 1140 UT, the
Fig. 4.3 Plasma ion pressure during the 22 March 1979 substorm

Fig. 4.4 Plasma ion density during the 22 March 1979 substorm
Fig. 4.5 Tail Magnetic field during 22 March 1979 substorm.

Fig. 4.6 log $P_i$ vs. log $N_i$ for 22 March 1979 substorm
disturbances start to subside marking the recovery phase. And at ~1200 UT, the full recovery is thought to occur and the substorm activity is over.

4.5.1 Pressure - Density Relations and polytropic index

In pursuit of finding the thermodynamic qualities of PS during the selected substorm, the logarithmic values of $P_i$ are plotted against those of $N_i$ in Fig. 4.6. The scatter diagram shows a sufficiently good correlation with a correlation coefficient of $r = 0.7673$. The polytropic index $\eta = 0.721$ (From Eqn. 4.5, the slope of the regression line gives the polytropic index). This is much less than that required for the adiabatic exchanges ($\eta = 1.67$ or $5/3$). i.e, the result proposes a non-adiabatic PS at $13 - 15 R_E$ during the selected event. It must be noted that according to Baumjohann (1993), if $\eta < 1.67$, there is a cooling mechanism in the sheet which makes it non-adiabatic. Thus, it seems, on an average, a cooling occurs at $13 - 15 R_E$ during the full course of a substorm. But there are many controversies over the polytropic index at different situations (Baumjohann and Paschmann, 1989, Huang et al. 1989, Goertz and Baumjohann, 1991, etc.). And hence a better understanding of the heat exchange processes is made in the next section using the entropy profiles.

4.5.2 Specific entropy

In any adiabatic change, the specific entropy $S$ should remain constant, or $S$ can be treated as an adiabatic invariant. The quantity is known to be proportional to $P_i / N_i^{5/3}$ (Goertz and Baumjohann, 1991; Paterson et al. 1995) and is plotted for the event, in Fig. 4.7. The entropy is found to be more
Fig. 4.7 Specific entropy parameter for 22 March 1979 substorm.
or less a constant during the growth phase without showing much variation from the pre-growth phase values. But it is highly varying in the expansion phase. Entropy has small but considerable fluctuations in the recovery phase too.

The specific entropy during growth phase denotes a balanced heat exchange in the $13 - 15 \ R_E$ NEPS. i.e., the heating of the sheet by SW input is balanced by the dissipations due to different cooling processes as predicted by the driven model of energy transfer. According to this model (Perreault and Akasofu, 1978), once the dayside reconnection interconnects the SW and geomagnetic field lines, the interplanetary electric field is directly applied to the ionosphere, driving electric currents. Divergences in the electric field and discontinuities in the ionospheric conductivity cause field aligned currents to flow. Changes in these currents are responsible for geomagnetic activity. The model suggests that southward IMF enhances the SW coupling and hence various currents. The rise in the associated field aligned currents develops a field aligned potential drop, which accelerates electrons. This increases the ionospheric conductivity and in turn the field aligned currents. This instability and subsequent saturation denote the expansion phase of the substorm. The driven model, thus, does not account for a considerable time delay between the beginning of the dayside reconnection (SW input) and the commencement of magnetospheric energy release into the ionosphere. Or whatever energy, assumed to be accumulated in the NEPS during the growth phase, is transferred entirely into the atmosphere without much time delay.
The fact that the entropy is a constant with respect to time implies that there is hardly any accumulation of energy in NEPS (as any accumulation would have raised the entropy level). Hence, NEPS acts only as a passage for energy from SW into ionosphere and atmosphere. Also, it is noted that there is an adiabatic transition even at a disturbed condition such as the growth phase.

The high degree of entropy fluctuations exhibited during the expansion phase points to a rather complicated way of heat transactions. The transitions are obviously non-adiabatic with the entropy falling to as low as $6.82 \times 10^{-21} \text{ Pa m}^5$ ($\log \alpha = -20.17$) and rising to as high as $3.14 \times 10^{-17} \text{ Pa m}^5$ ($\log \alpha = -16.5$). Thus NEPS sometimes gets heated up and some times cooled down. Hence, there is a random imbalance between the heating and dissipation levels. In Chapters 2 and 3, it was reported that the heating of NEPS occurs through either convection or conduction (both electrical and thermal). The cooling can be caused by the precipitation of ions into the atmosphere, outward diffusion of particles and energy and also by the emission of Poynting flux from the sheet (Goertz and Baumjohann, 1991). It is to be worth noting that for the 22 March 1979 substorm, at the former expansion phase (1055 UT to 1115 UT), the average entropy level is slightly less than that at the latter expansion phase (1115 UT to 1140 UT). Thus it turns out that the dissipation dominates heating at the former phase and vice versa at the latter phase.

The entropy fluctuations as seen in the recovery phase are of decreasing amplitude and within minutes, the oscillations die out and a more or less constant entropy level results.
An important feature of Fig. 4.7 is that the average entropy during the recovery phase is greater than that at the growth phase. Hence, there is definitely a net gain of heat for the NEPS at the end of the substorm. Evidently, the heating processes are strong enough to dominate dissipations at latter expansion phase and the recovery phase. The substorm is essentially a heating process and hence is a non-adiabatic event with the exception that the growth phase is roughly adiabatic.

4.6. Conclusion

It is evident that the NEPS behaviour at distances below $10 \, R_E$ can be non-adiabatic at substorm onsets. This shows the imbalance in the conduction and heating rates during disturbed times at the geosynchronous site. The acceleration of particles at the reconnection site, the increasing electric field, the realignment in the magnetic field configuration, the different PS waves, particle losses into the ionosphere, etc., are thought to be contributing well to the non-adiabaticity of PS. The study also brings out that the NEPS obeys a hybrid equation of state not only at quiet times, but also at disturbed conditions such as onsets as well. The behaviour of the sheet was closer to the one obeying constant magnetic moment equation of state. This suggests that in describing the dynamics of the NEPS, the increasing magnetic field is more important than the increasing particle velocities due to reconnection. Thus the study is an effort to analyse the various electromagnetic and thermodynamic mechanisms, which induce non-adiabatic heating in NEPS.
The results reported in Sec. 4.5 confirm that the substorm event, in general, is a non-adiabatic event beyond 10 \( R_E \) as predicted by Huang et al. (1992), though the adiabatic behaviour noted during the growth phase does not agree.

For the selected substorm, the obtained polytropic index \( \eta = 0.721 \) did not mean a resultant cooling in the NEPS as predicted by Baumjohann (1993). The disturbed periods have \( \eta < 1.67 \), in contrast with the results of Baumjohann (1993). From these observations, \( \eta \) does not seem to be a good reflector of adiabaticity (Baumjohann and Paschmann, 1989, Huang et al. 1989, Goertz and Baumjohann, 1991). This outcome emphasizes the use of specific entropy as a better measure of adiabatic behaviour. Even though a stepwise increase in specific entropy as predicted by Baumjohann (1993) is not observed during the selected substorm, a gradual rise in entropy from growth to recovery (with the exception that it falls frequently during the expansion phase) can be found. This rise in entropy definitely accounts for the non-adiabaticity. And the reason for the non-adiabatic heating of the NEPS could be current sheet acceleration, ULF wave absorption, neutral line acceleration, etc. The constant entropy obtained during the growth phase supports the concept of dissipations as suggested in the driven model of energy transfer. It was quite a new observation to note that the NEPS has no significant role in the heat transfers during growth phase. Thus the role of the growth phase during the selected substorm seems to be unknown. The entropy profiles behave as if the disturbance started at the expansion onset. The solution to these issues needs many more observations and analysis and a definite answer for the substorm triggering mechanisms is yet to come.