Chapter 3

Substorm time Electrical Conductivity of the Plasma Sheet and its association with Geomagnetic Activity

3.1 Introduction 75
3.2 Electrical conductivity 77
3.3 Conductivity at substorm onsets 78
  3.3.1 Onsets selected and data used 78
  3.3.2 Results and discussion 79
3.4 Conductivity during single substorm 82
3.5 Conclusion 85
3.1 Introduction

The geomagnetotail plasma sheet is a magnetic domain carrying various currents and particle motions, which contribute to its dynamics and thermodynamics. Most of the energy transactions, dissipations, bulk flows, field configuration, etc., are directly or indirectly connected to the currents and conductivity of this site. The dissipation of energy during substorms can be directly adduced by the examination of ionospheric and ring current parameters and by the in situ observations of hot plasmas and energetic particle populations accelerated by substorm processes (Baker et al. 1985). The interchange instability of the magnetosphere–ionosphere interaction caused by the effect of field-aligned current was studied by Kozlowski and Lyatski (1994). The formation of ring current in the plasmasphere by the interaction of energetic electrons and Alfvén waves was studied by Bespalov and Demekhov (1994). Observations show that current disruptions and bursty bulk flows are qualitatively similar phenomena in the near earth tail, both being associated with poleward moving auroral substorms (Angelopoulos et al. 1999). The auroral currents measured by AE indices are produced by the solar wind generated Poynting flux. This energy, which gets absorbed in PS, is partly precipitated into the ionosphere and partly injected into the ring currents. The rates at which these forms of energy flux are absorbed and transmitted to the ionosphere depend on different characteristics of PS like its conductivity (electric and thermal), the magnetic field, the temperature, the thickness of PSBL, etc., (Smith et al. 1986).
PS heating/dissipation processes and the electrical conductivity are well related. Consider the event of a perturbation displacement of a particle in the z-direction through PS along a closed field line with antisunward propagating waves having wave vector \( k \) with components \((k_x, k_y, 0)\) and frequency \( \omega \). The waves perturb a field line with a parallel wave number \( k_\parallel \) and excite oscillations of this field line at its resonance frequency \( \omega_A \). If \( \omega = \omega_A \), oscillations will grow to a very high amplitude and a resonance layer develops between the lobe and the neutral sheet. The energy dissipation rate \( Q \) integrated over the resonance layer and the wave temperature \( T_w \) are given by Goertz et al. (1991) as

\[
Q = \frac{4\pi^2 \Delta z P_{fz}}{\mu_0 \left[ \left( \frac{T}{T_w} - 1 \right)^2 + \pi^2 k_\parallel^2 \Delta z^2 \right]} \quad (3.1)
\]

\[
T_w = \frac{1}{2} m_i \omega^2 \left( \frac{k_\perp / k}{k_\parallel} \right) \left( 1 + \frac{2}{\beta} \right) \quad (3.2)
\]

where \( \Delta z \) is the scale length of the gradient of the Alfvén speed in the resonance layer where the absorption of ULF waves occur, \( P_{fz} \) a function of magnetic fluctuations in the lobe, \( T \) the temperature on PS side of the resonance layer, \( m_i \) the average ion mass and \( \beta \) is the average plasma \( \beta \) parameter. One general feature of Eqn. 3.1 is that the heating rate has a maximum value at \( T = T_w \). As the heating rate can never be zero, a steady state for the plasma temperature can be reached only when the heating is balanced by conduction or convection losses into the ionosphere.
An attempt, to analyze how conducting properties of the sheet affects the losses and dissipation of energy into the ionosphere during substorm period, is made in this Chapter. The specific electrical conductivity \( \sigma \) of the plasma at PS at selected substorm onsets (Table 2.1) have been calculated and the variations of AE and Dst indices with \( \sigma \) have been analysed. The dependence of the conductivity on the sunspot numbers and the plasma ion pressure were also checked. The conductivity was calculated also for the full course of a substorm and its influence on ionospheric energy dissipation was examined.

### 3.2 Electrical conductivity

Plasma particles, which execute motions, are susceptible to collisions that induce a resistivity to the sheet. Resistivity is generated in collisionless plasmas too, due to wave-particle interactions. Current-driven instabilities can generate waves, which mediate momentum exchange between particle species and thus limit or retard the driving current. A finite resistivity will cause particle and field diffusion in plasma and the resulting induced currents can cause Ohmic heating (Joule heating).

Plasma sheet is the site of various currents and hence the electrical conductivity (or resistivity) of the sheet is of much importance. Current diversions, especially during substorms, and the magnitude of cross-tail current are greatly dependent on the electrical conductivity. Analytical estimates of resistivity due to electrostatic current-driven ion acoustic waves were compared with Vlasov simulation results (Watt et al. 2002). The specific electric conductivity \( \sigma \) of the plasma as given by Akasofu (1977) can be written as
\[
\sigma = \frac{12\pi^{3/2} e_0^2 k_B^{3/2} T_e^{3/2}}{2^{1/2} m^{1/2} e^2 \ln D}
\] (3.3)

where \( \ln D (\sim 26) \) is a function of Debye length and impact parameter. \( T_e \) can be found out if one knows \( \beta_e \), magnetic field and number density (See Sec. 2.5.1 for details) using which \( \sigma \) can be estimated.

Since Eqns. 3.1 and 3.3 are functions of plasma temperature, the specific conductivity should have obvious influence on the heat dissipation rate. Since from Eqn. 3.3, the magnitude of \( \sigma \) is larger for high temperature plasma, dynamical phenomena in plasma can often be described in the approximation of infinite conductivity or perfect conduction. Such perfectly conducting or collisionless plasmas will be tied to the magnetic field lines, i.e., any two elements of such a plasma that lie initially on a given field line will still lie on the same field line after an arbitrary motion of the plasma.

### 3.3 Conductivity at substorm onsets

#### 3.3.1 Onsets selected and data used

The plasma electron beta parameter \( \beta_e \), electron density \( N_e \), ion pressure \( P_i \) and PS field intensity \( B \) for 22 substorm onsets derived from GEOS-2 observations have been collected (Table 2.1). AE, Dst and \( \chi \) used in the study are also shown in the table.
3.3.2 Results and Discussion

a) Electrical conductivity and AE index

As conduction and currents contribute significantly to the electrodynamics and energy transfer in the PS, an investigation into the effect of PS conductivity on the field aligned currents and AE index is of interest. The electrical conductivity at substorm onsets was calculated using Eqn. 3.3. The auroral electrojet indices AE was found to be maximum for onsets with moderate conductivity (Fig. 3.1). For onsets with $\sigma < 1.2 \times 10^9 \text{ } \Omega^{-1}\text{m}^{-1}$, the larger the conductivity, the larger the AE and for onsets with $\sigma > 1.2 \times 10^9 \text{ } \Omega^{-1}\text{m}^{-1}$, the larger the $\sigma$, the lower is the AE. The observed variations can be explained on the basis of the fundamental relationship between the field aligned currents and the AE index. An increased conductivity substorm onset will cause high intensity field aligned/Birkeland currents in the NEPS. The currents include more equatorward ring currents and the region 2 Birkeland currents (Iijima and Potemra, 1978). These currents are directed down to the ionosphere on the dusk side and up from the ionosphere on the dawn side. These increased currents will in turn cause high magnetic disturbances, thereby raising the value of the AE index. Thus AE at onsets increases with $\sigma$ at onsets. But for events of very high $\sigma$, the high conductivity and the resulting high current will produce an increase in the temperature of PS. According to Smith et al. (1986), events with higher temperature will possess a higher rate of energy flux absorption. Thus the NEPS absorbs energy/particle flux with a heavier rate for events with extremely higher conductivity. This in turn will reduce the current (which is constituted by moving free charges).
Fig. 3.1 AE index at different onsets plotted against Conductivity
reducing the AE. This explains the drop in the AE for very high $\sigma$ events. Collisionless conductivity and stochastic heating of the PS was well analysed by Horton and Tajima (1991).

**b) Electrical conductivity and Dst index**

The dependence of ring current intensity on PS electrical conduction is discussed with reference to the variation of storm index Dst with $\sigma$. Dst magnitudes for substorm onsets with higher conductivities were observed to be higher (Fig. 3.2). A higher conductivity at the onset at PS obviously enhances the currents and more current is now diverted into the ionosphere. The diverted cross tail current can induce energy dissipation either as Joule heat or as ring currents. An onset time with a higher conductivity will thus possess a higher ring current intensity too. This results in a higher Dst magnitude. The result agrees well with that of Dessler and Parker (1959) according to which Dst is proportional to the number of drifting particles those create the current. A higher conductivity at PS plasma adds to this total energy of the drifting particles and hence raises the Dst magnitudes. Also since ring current emphasizes those components of the particle distributions that contribute importantly to the current density, which, for non-relativistic particles is proportional to the energy density, an onset with higher conductivity corresponds to a higher energy density in the ionosphere.
Fig. 3.2 Dst values at different onsets plotted against Conductivity.
c) Ion pressure and Electrical conductivity

Pressure variations can cause corresponding changes in temperature and hence in the conductivity of onset time PS. The electron specific conductivity is plotted against the ion pressure at selected onsets in Fig. 3.3. It is evident from the plot that the higher the pressure at onsets, the higher the conductivity. An increased pressure always denotes increased particle density and temperature. This hike in density and temperature is responsible for higher conductivity.

d) Sunspot number and Electrical conductivity

It is well known that solar activity, in association with many factors, controls the particle properties of PS and hence the dependence of PS electrical conductivity on the sunspot number is of scientific interest. Conductivity is plotted against sunspot number corresponding to different onsets in Fig. 3.4. A higher value of the sunspot number is observed to raise the onset time conductivity. Sunspots are clear manifestations of solar activity. The higher the sunspot number the higher is the influence of solar activity on earth. And in that sense, higher solar activity causes a higher conductivity for the PS. This can be due to the obvious relationship between solar activity and number density of PS particles. Sunspots are the measures of solar activity and can be correlated to electrical, magnetic and meteorological environment of the earth (McCormac, 1983). Also, the geomagnetic events are strongly related to the solar magnetic field and hence to the sunspot number (Pevtsov and Canfield, 2001). Thus an increased sunspot number causes an increased particle density which in turn results in a higher temperature and hence a higher conductivity.
Fig. 3.3 Conductivity at different onsets plotted against Plasma ion pressure.
Fig. 3.4 Conductivity at different onsets plotted against Sunspot number.
3.4 **Conductivity during single substorm**

Electrical conductivity of the plasma at the ISEE 2 site (13-15 \(R_E\)) during the full course of 22 March 1979 substorm has been found out and its variations with various parameters have been analysed in this section. The ionospheric impacts of conductivity variations have been addressed with reference to the Joule heat production rate and the total magnetospheric heat output. It is well known that the storage and sudden release of energy throughout the substorm interval involves the process of energy flow from the solar wind through the outer magnetosphere into the ionosphere and the ring current. Therefore, to achieve a true measure of magnetospheric energy dissipation, one has to examine parameters explicitly related to ionospheric and ring current dissipation. The Joule heat production rate in the ionosphere and the total magnetospheric energy output are well suited for the purpose.

The substorm interval selected was the one explained in Sec. 2.6.1. The electron temperature \(T_e\) measured by ISEE 2 for the selected substorm period has been collected. The satellite was at a distance of 13-15 \(R_E\) downtail, from the centre of the earth at a local time 0200 LT during the period. This makes it suitable for measuring PS temperatures (Paschmann et al. 1985). The electrical conductivity of plasma at the site was calculated using Eqn. 3.3 and is plotted in Fig. 3.5.a. The following observations can be made from the figure:

1. The conductivity is more or less a constant during the growth phase of the substorm with an average value \(\sim 0.5 \times 10^7 \Omega^{-1} \text{ m}^{-1}\).
2. For about 20 minutes after the expansion onset (the former expansion phase), the conductivity does not show considerable variations.

3. During the interval 1115 UT to 1140 UT, (latter expansion phase), the conductivity increases considerably with values reaching even $6.5 \times 10^7 \Omega^{-1} \text{ m}^{-1}$ at the end of expansion phase.

4. Conductivity falls towards growth phase values during the recovery phase (i.e., from 1140 UT to 1200 UT).

These variations in conductivity will have enormous effects on the magnetosphere and the ionosphere, especially at times of substorms. The energy dissipations from the magnetosphere to the ionosphere take place both at the growth phase and the expansion phase of a substorm, the latter being stronger than the former (Baker et al. 1985). All these dissipations strongly involve various currents and in this context conductivity profiles are important. Joule heat at the ionosphere and the entire magnetospheric energy output function $U_T$ (Akasofu 1981, Baker et al. 1983; 1985) have been considered as a measure of the energy dissipation from the magnetosphere into the ionosphere. These parameters are plotted in Figs. 3.5.b and 3.5.c respectively.

As is evident from the comparison of Figs. 3.5.a and b, the total Joule heat rate follows the variations in electrical conductivity. During the growth phase and the former expansion phase, there is almost a constant Joule heat rate at the ionosphere whereas after 1120 UT (~5 min after conductivity started to rise), the Joule heat shows a sharp increase till the end of expansion phase (~1140 UT). During the recovery phase the heating is reduced even though a
Fig. 3.5.a Electrical conductivity during 22 March 1979 substorm

Fig. 3.5. b Joule heat production rate during 22 March 1979 substorm. (Baker et al., 1985)
Fig 3.5.c Total Magnetospheric output function during 22 March 1979 substorm (Baker et al., 1985)
spike occurred at ~1200 UT (Fig. 3.5.b.). The ionospheric heating is attributed to increased ionospheric currents and electric fields. It is a fact that during the substorm expansion phase, the cross tail currents are diverted to the auroral ionosphere. Examination of plasma flows in the quiet time PS reveals that this tail current disruption controls the trigger and development of the substorm (Ohtani et al. 2002). The increased conductivity of the plasma observed at the latter expansion phase of the substorm enhances the diverted current conduction, which in turn raises the current density in the ionosphere. The ionospheric Joule heat production which is proportional to \( jE \) (\( j \) and \( E \) being the current density and the electric field respectively) thus shows a huge increase during the latter expansion phase. During the recovery phase the conductivity and hence the Joule heat starts to return to their pre-onset values.

The total magnetospheric output function \( U_T \) (Fig. 3.5.c) in contrast, does not show a one to one correspondence with the conductivity variations. But generally, one can see that the total magnetospheric output is very large at times of higher plasma conductivity. It can be noted that \( U_T \) is higher for the period 1030 UT to 1200 UT and the conductivity (Fig. 3.5.a) has higher values for the period 1115 UT to 1200 UT. The \( U_T \) parameter considers both auroral and ring current dissipation terms. The enhanced electrical conductivity can enhance both of these diverted currents, which will cause an increased \( U_T \) function. But the observed larger \( U_T \) for smaller conductivity (at the growth and former expansion phases) needs further explanation. It is noteworthy (from Fig. 3.5.d) that the solar wind energy input (into the magnetosphere) function measured by IMP 8 has higher values at the growth phase and the
Fig 3.5.d  Solar wind energy input into the magnetosphere during 22 March 1979 substorm (Baker et al., 1985)
former expansion phase. As per the driven model (Sec 1.11), there can be dissipation of magnetospheric energy into the ionosphere even when the loading of energy proceeds. It can be this dissipation of energy that makes $U_T$ higher even before the conductivity has risen. This can also be attributed to the low level dissipation as predicted in the modified unloading model (Sec 1.11). Also it is to be considered that $U_T$ is only a rough estimate of ring current and ionospheric dissipation terms and it has very defined limitations (Baker et al. 1983).

Another important point that can be noted from Fig. 3.5.a is that there is a time delay between actual onset time of substorm and the beginning of an increase in conductivity. The former takes place around 1055 UT and the latter starts at around 1115 UT (with a time delay of $\sim$20 min.). This can be treated as the typical time scale/delay between the expansion phase onset and the beginning of the enhancement in the diverted cross tail current through the auroral ionosphere.

### 3.5 Conclusion

Electrical conductivity of the NEPS was proved to be an influencing factor in deciding many of the magnetic field as well as plasma parameters. The conductivity calculated for different onsets at GEOS 2 and for the full course of a substorm at ISEE 2 site brings out many outstanding features of PS electrodynamics. The substorm time energy transactions, the current diversions, etc., were shown to be dependent on the conductivity. Efforts have also been made to correlate the solar activity with the conductivity.
It may seem that the results reported in this Chapter (see also Prince et al. 1997a) are against the current disruption model (Lui et al. 1988) of substorms. As per Lui's model, combination of lower hybrid waves (Lui et al. 1990) produced due to kinetic cross-field streaming instability and lower hybrid drift waves produced due to lower hybrid drift instability causes an anomalous resistance in PS. This resistance disrupts the cross-tail current. But the current must continue to flow and it accomplishes this by diversion along field lines particularly those of substorm current wedge. So it naturally follows from the model that a higher conductivity (lower resistivity) should reduce the current diversion. But from the results obtained in this Chapter, especially in the single substorm analysis, it was confirmed that a higher conductivity enhances the ionospheric current. The answer to this problem is that the computed conductivity is of more near earth PS in the 13-15 $R_E$ region. This is the region where the already diverted (due to higher resistivity of Lui's (1988) current disruption model) cross-tail currents flow. Or, this is the region where field aligned/Birkeland currents exist. Therefore, the higher conductivity of the region makes the conduction of these currents easier resulting in high ionospheric dissipations. Meanwhile, the currents were being diverted continuously due to the higher resistivity at the more distant PS. That is, the outcome of the present study is not against Lui’s model. The computation and examination of electrical specific conductivity at the diverted path of the cross-tail currents, is quite new in the magnetospheric explorations and hence this study is a significant step in the process of exploration of substorms and the related current models.