## Chapter 5

### MT index at Substorm Onsets and at 22 March 1979 Substorm

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5.1 Introduction

The activity indices play a significant role in the exploration and understanding of various solar terrestrial phenomena. They reflect different features of the sun-earth system and explain the observational facts associated with many physical changes taking place inside it. An index can be simply derived from some important physical parameters related to phenomena causing some sorts of disturbances in the system. The indices presently in use can be broadly classified into two- one derived from ground-based observations and the other from high altitude spacecraft observations.

The first group characterizes the intensity of specific current systems or a mixed input from different current systems. The well known AE, Dst, $K_p$, etc., indices fall in this group. The second group of indices denotes the energy input from SW or the magnitude of compression of the geomagnetosphere by SW. The IMF $B_z$ component, SW dynamic pressure $P_d$, SW – magnetosphere coupling function $\epsilon$, etc., are some of the parameters included in this group. The availability of these parameters depends mostly on the motion of the satellites and their distribution in space.

The existing indices fail to reflect an essential characteristic of magnetic activity, viz., the magnetic configuration. The important role of the magnetic field and its global structure is well recognized. It plays the role of a road map in the magnetosphere (Stern and Tsyganenko, 1992) by controlling the dynamics and distribution of the plasma and by connecting the ionosphere and magnetosphere to form a united magnetosphere-ionosphere system. In any problem of magnetospheric dynamics, the precise knowledge of the
magnetospheric configuration is significant. The available activity indices can give acceptable values for the field magnitude (Maltsev and Ostapenko, 2001). But, they are known to be poor indicators of the concurrent magnetospheric configuration (Fairfield, 1991; Malkov and Sergeev 1991; Campbell, 1996). Therefore a new index to represent the missing property was proposed by Sergeev and Gvozdevsky (1995).

The new index called $MT$ index (magnetotail index) is suggested to be the predictor of the instantaneous magnetospheric configuration. The index is derived from the equatorward boundary of isotropic precipitation of energetic particles. In this Chapter, the association between the calculated $MT$ and the measured inclination of the tail field at substorm onsets has been included. A total of 22 substorm onsets (Table 2.1) were selected for the analysis. The work presented in this Chapter reveals that $MT$ in the original form does not reflect the tail field configuration at the onsets. A correlation analysis of different parameters, viz., the tail magnetic field $B$, field inclination $I$, plasma $\beta$, plasma ion pressure $P_i$ and the plasma ion density $N_i$ with the $MT$ index was also done. $MT$ index during the full course of 22 March 1979 substorm was found out and the $MT$ profile is explained.

5.2 Isotropic Boundary

A low altitude polar spacecraft crossing the auroral zone generally detects a region of energetic proton precipitation. This domain is having a well-defined equatorward boundary known as isotropic boundary (IB), which is rather sharp with only a few tenths of degree in latitude. The IB
positions were observed to be at lower geomagnetic latitudes for particles of higher energy or mass. This IB of energetic particles measured at low altitudes is interpreted as the boundary between regions of adiabatic and chaotic (non-adiabatic) particle motions controlled by the magnetic field in the equatorial tail current sheet (Sergeev and Gvozdevsky, 1995; Gvozdevsky and Sergeev, 1996). Therefore finding out the IB position provides an indirect method to evaluate the magnetic field configuration and to probe the magnetic field gradients in the magnetotail. The existence of such an isotropic boundary can be interpreted in terms of Tail Current Sheet (TCS) scattering mechanisms (Sergeev et al. 1993).

Particles moving on closed field lines, which obey pitch angle distribution, can undergo collisions in the ionosphere causing strong flux depletion in the loss cone. This depleted loss cone will be conserved for those particles moving adiabatically (provided there is no wave-particle interaction). Any non-adiabaticity in particle motion can result in the filling of the loss cone. The non-adiabaticity exhibited by substorm affected geosynchronous PS (Prince et al. 1998) can be one such typical situation. The strongest deviation from the adiabatic nature occurs at the equator in the central current sheet for those particles undergoing bounce motion at lower altitudes (having small equatorial pitch angles). And adiabaticity is primarily controlled by the equatorial value of the ratio $R_e/\tau$, where $R_e$ is the curvature radius of the field line and $\tau$ is the particle gyro radius. It can be shown that
\[ \frac{R_c}{\tau} = \frac{B_x^2}{G \frac{dB_x}{dz}} \]  

(5.1)

where \( G \) is the particle rigidity and \( B_x \) and \( B_z \) are the components of equatorial tail magnetic field. Numerical simulation studies conducted by Sergeev et al. (1983) and Sergeev and Malkov (1988) give the condition for pitch angle scattering (scattering to the centre of the loss cone and thereby filling it) as

\[ \frac{R_c}{\tau} \leq 8 \]  

(5.2)

or

\[ \frac{B_x^2}{G \frac{dB_x}{dz}} \leq 8 \]  

(5.3)

Due to the well-known decrease of \( B_z \) with distance into the tail, the closed field line region is divided into two parts - the inner one where \( R_c/\tau > 8 \) (adiabatic) and the outer part where \( R_c/\tau < 8 \) (non-adiabatic). In the inner region, the depleted loss cone is conserved, whereas in the outer region, the loss cone is refilled because of non-adiabatic particle motion when crossing the equator. The boundary between the two regions is the isotropic boundary \( (R_c/\tau = 8) \). The two domains of the tail are shown in Fig. 5.1. The isotropic boundary, in other words, corresponds to boundary between regions of empty (depleted) loss cone and filled loss cone pitch angle distributions. Therefore, detecting IB by a low altitude polar spacecraft symbolizes the fact that a
Fig 5.1 Adiabatic and non-adiabatic regions of the magnetotail

(Sergeev et al., 1993)
corresponding magnetic field condition exists in the equatorial section of the boundary (or field line). Increase in current or thinning of the current sheet pushes the equatorial position of the boundary \((R_e/\tau = 8)\) earthward. Also, the increased tailward stretching of field lines causes ionospheric projection of any equatorial point to move equatorward. Together these effects result in an equatorward drift of the IB latitude with increase in tail current and hence explain the causal relationship between IB and tailward stretching of the magnetospheric magnetic field (magnetic field configuration) (Sergeev and Gvozdevsky, 1995).

Many studies have been carried out so far to verify TCS scattering mechanism. For example, the IB position observed on several quiet time inbound passes of the OGO-5 magnetospheric spacecraft was compared with the positions predicted from the magnetic field observations on the same spacecraft (West et al. 1978) and a very good agreement between the predicted and the observed values was obtained. A comparison between the predictions from magnetospheric models (using Eqns. 5.2 and 5.3) and the observed values was made by Imhof (1988). Also, the magnetic field at GOES 2 was computed from the IB positions detected by NOAA spacecraft and was compared with the fields actually observed (Sergeev et al. 1993) at GOES 2 and the results showed that the tail magnetic field effectively controls the IB latitude (with a correlation coefficient as good as 0.9).
5.3 MT index

A new measure of instantaneous geomagnetotail field, the $MT$ index, is extracted from the position of the isotropic boundary. It has been shown that the IB latitude ($IBL$) does not remain constant in all local times and the modeled daily (0-2300 hrs MLT; MLT being the magnetic local time) variation (using T89 model) is $\sim 4$ to $8^\circ$ CGLat (corrected geomagnetic coordinate system is used and CGLat is the corrected geomagnetic latitude) (Sergeev and Gvozdevsky, 1995). Thus for introducing a single quantity ($MT$ index) characterizing the IBL, this daily variation has to be subtracted. The hemispherical differences of IBL are reasonably small ($0.5-1^\circ$ CGLat) within about 0400 hrs MLT around a symmetry line of 2300 hrs MLT, i.e. from 1900 to 0300 hrs MLT. So in the derivation of the $MT$ index, this MLT sector alone is considered.

The $MT$ index is defined as the invariant latitude of the isotropic boundary (IB) of energetic protons reduced to the midnight meridian and is given by

$$MT = IBL - A_{l(\text{av})}\{1 - \cos[\pi(MLT - MLT_0)/12]\} \quad (5.4)$$

where $IBL$ is measured at some $MLT$ in the sector 1900-0300 hrs. $A_{l(\text{av})}$ ($= 4.3^\circ$ CGLat) is the amplitude and $MLT_0$ ($= 2301$ hrs) is the phase (Sergeev and Gvozdevsky, 1995). A statistical study carried out using data from the polar sun-synchronous NOAA spacecraft (TIROS, NOAA-6 and 7) operating at an altitude of around 850 km, gives a simple first harmonic cosine approximation
(Sergeev and Gvozdevsky, 1995) for IBL as

\[ IBL = A_0 - A_1 \cos(\pi(MLT - MLT_0)/12) \]  \hspace{1cm} (5.5)

The parameters \( A_0, A_1 \) and \( MLT_0 \) of this approximation have different values depending on the different solar activity conditions. A statistical grouping of the data into 16 clusters based on different AE indices and \( P_d \) (SW dynamic pressure) ranges was done and accordingly there are 16 values each for \( A_0, A_1 \) and \( MLT_0 \). These values are given in Table. 5.1

\( MT \) at different substorm onsets (Table 2.1) and during 22 March 1979 substorm have been extracted in this Chapter. AE and \( P_d \) required for the computations were collected from WDC C2 for Geomagnetism Data Book and Interplanetary Medium Data Book respectively. This data was grouped into 16 clusters as done by Sergeev and Gvozdevsky (1995). Using the characteristic values of \( A_0, A_1 \) and \( MLT_0 \) for each group, \( MT \) was calculated using Eqns. 5.4 and 5.5. As an example, Fig. 5.2 shows \( MT \) index with a temporal resolution of 1 hr for the month of January 1979. Influence of a time delay associated with bounce motion, on \( MT \) index was studied by Prince et al. (2000).

5.4. \textbf{MT at onsets}

The \( IBLs \) and \( MTs \) at different \( MLTs \) (from 1900 to 0300 hrs) at 22 substorm onsets (Table 2.1) were found out using the harmonic approximation discussed in Sec. 5.3 above and the respective averages were taken. The dependence of \( MT \) on \( B, I, \beta, P_i \) and \( N_i \) has been analyzed.
Table 5.1

Parameters of Harmonic Approximation for different ranges of AE and $P_d$

<table>
<thead>
<tr>
<th>AE (nT) ↓</th>
<th>$P_d$ (nPa) →</th>
<th>&lt;1.33</th>
<th>1.33-1.67</th>
<th>1.67-2.00</th>
<th>&gt;2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100</td>
<td>$A_0$</td>
<td>69.01</td>
<td>69.48</td>
<td>69.60</td>
<td>69.06</td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
<td>3.42</td>
<td>4.72</td>
<td>4.50</td>
<td>5.49</td>
</tr>
<tr>
<td></td>
<td>$MLT_0$</td>
<td>23.20</td>
<td>23.52</td>
<td>23.78</td>
<td>23.72</td>
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<td>$A_0$</td>
<td>68.73</td>
<td>68.72</td>
<td>68.41</td>
<td>68.44</td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
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<td>4.17</td>
<td>4.49</td>
<td>5.52</td>
</tr>
<tr>
<td></td>
<td>$MLT_0$</td>
<td>23.08</td>
<td>23.25</td>
<td>23.45</td>
<td>23.50</td>
</tr>
<tr>
<td>200-400</td>
<td>$A_0$</td>
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<td>67.97</td>
<td>67.87</td>
<td>67.43</td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
<td>3.95</td>
<td>3.64</td>
<td>4.27</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td>$MLT_0$</td>
<td>22.74</td>
<td>23.17</td>
<td>23.35</td>
<td>23.33</td>
</tr>
<tr>
<td>&gt;400</td>
<td>$A_0$</td>
<td>66.66</td>
<td>66.84</td>
<td>66.11</td>
<td>34.79</td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
<td>3.35</td>
<td>3.58</td>
<td>4.77</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>$MLT_0$</td>
<td>22.73</td>
<td>22.50</td>
<td>22.38</td>
<td>22.53</td>
</tr>
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</table>
5.4.1 Field inclination

The magnetic field inclination $I$ required for the analysis can be calculated from parameters in Table 2.1 as follows:

The inclination angle of a field line as given by Quinn and McIlwain (1979) is

$$\tan I = 2 \tan \lambda + b \sin q \lambda$$  \hspace{1cm} (5.6)

where $\lambda$ is the magnetic latitude of field line, $b$ represents the dipole field ($= 0$) or a non-dipole field ($\neq 0$) and $q = 4$ (Mauk, 1986).

Also according to this model,

$$\frac{B}{B_0} = \frac{1}{\cos^5 \lambda} \left[1 + (2 \tan \lambda + b \sin q \lambda)^2\right]^{1/2} \exp\left[2\left(\frac{b}{q}\right)\left(1 - \cos q \lambda\right)\right]$$  \hspace{1cm} (5.7)

where $B$ is the tail magnetic field strength at $(R, \lambda)$, $R$ the radial distance from the centre of the earth to the field line at magnetic latitude $\lambda$ and $B_0$ is the field strength of the same field line at the equator. The solution of Eqn. 5.7 [after substituting values of $\lambda$ (Pu et al. 1992)] using numerical methods gives the value of $b$, which when substituted in Eqn. 5.6 gives the field inclination $I$.

5.4.2 Results and Discussion

$MT$ is plotted against the tail magnetic field $B$ and the field inclination $I$ in Figs. 5.3 and 5.4 respectively. It is obvious from the figures that there is no significant correlation between $MT$ and $B$ or between $MT$ and $I$ (correlation coefficients $-0.4103$ and $0.4210$ respectively). This result
Fig. 5.2 $MT$ index during January 1979

Fig. 5.3 $MT$ index vs. Tail magnetic field at substorm onsets
Fig. 5.4 $MT$ index vs. Magnetic field inclination at substorm onsets.

Fig. 5.5 $MT$ index vs. Plasma $\beta$ at substorm onsets.
Fig. 5.6 $MT$ index vs. Plasma ion pressure at substorm onsets

$r = -0.0671$

Fig. 5.7 $MT$ index vs. Plasma ion density at substorm onsets

$r = -0.1135$
looks rather unexpected as $MT$ was predicted to be a good indicator of instantaneous magnetic configuration and hence of $B$ and $I$. The plasma parameters such as plasma $\beta$, ion pressure $P_i$, and ion density $N_i$ also failed to give considerable dependence on $MT$. This is evident in Figs. 5.5, 5.6 and 5.7.

As $MT$ is predicted to be a good indicator of the instantaneous tail magnetic field configuration, one may expect a nice correlation between $MT$ and $I$ (and $B$) and also between $MT$ and the plasma parameters. The reasons for the unexpected results obtained can be thought to be interrelated. The absence of a systematic relationship between $MT$ and $I$ or between $MT$ and $B$ can be the cause for the absence of a similar relationship between $MT$ and plasma parameters. The basis for this argument is that, the tail magnetic field in association with other factors play a very important role in controlling PS particle dynamics. For example, it has been shown that factors such as conductivity, wave temperature, etc., affect the particle motion in PS (Bindu et al. 1994 and Prince et al. 1997a&b). For the most part, PS lies on closed field lines and hence it is apt to think that the tail field has much influence on the dynamics of PS. Also, the plasma inflow from the mantle side towards the centre of the tail to obtain a balanced reconnection dynamics is, in fact, an $E \times B$ drift, which again depends on $B$. From this point of view, it follows that the relevant problem of the context is: why variations in $MT$ do not follow changes in $B$ or $I$ as expected?

The full process of a substorm takes place in three different stages – the growth, expansion and recovery phases (Sec.1.9). The energy extracted from SW is stored in the magnetosphere during the growth phase and the expansion
phase onset corresponds to the triggering of release of that stored energy. Hence, the temporal and spatial variations in the magnetic field and plasma parameters in the tail site are too rapid at the onsets. These short-term changes (within a few minutes), typical for the localized activation occurring during the expansion phase onsets result in a very complicated spatial configuration. This new configuration has a dynamical and localized character, which cannot be described satisfactorily by any known magnetospheric model. Thus such short-term localized perturbations cannot be characterized by any single parameter such as the $MT$ index. In other words, the temporal resolution required for the $MT$ index to represent such small time scale processes would be very small, which cannot be achieved by the present known methods of measurements and computations. And this can be the reason why $MT$ values do not follow variations in $B$ or $I$. The other plasma parameters such as plasma $\beta, P_t, N_i$, etc., at the onsets were also found to show no significant correlation with $MT$, because they are strongly influenced by $B$ and $I$.

### 5.5 Single substorm analysis

$MT$ index during the full course of March 22 1979 substorm was calculated and analyzed in this section. Fig. 5.8 is the $MT$ index variations during the event. IMP 8 SW data (McPherron and Manka, 1985) has been used for the extraction of the index. $MT$ shows a rapid fall during the growth phase, but it remains constant both at expansion and recovery phases. The magnetic field inclination $I$ as measured by the GOES 3 satellite is plotted in Fig. 5.9 (Baker et al. 1985). ($I$ is defined as the field colatitude in a dipolar co-ordinate
Fig. 5.8 Variation of $MT$ index during the 22 March 1979 substorm

Fig. 5.9 Variation of Field inclination at GOES 3 during the 22 March 1979 substorm
A dipole field at GOES 3 would have $I \approx 10^\circ$ and a tail-like field at the site would have $I \rightarrow 90^\circ$). Comparing Figs. 5.8 and 5.9 it becomes clear that $MT$ at expansion and recovery phases of this substorm, in no way, reflects the magnetic field inclination or configuration. The anti-correlation existing between $MT$ and $I$ during the growth phase of the substorm is depicted in Fig. 5.10 (correlation coefficient $= -0.9312$). Thus the greater the stretching of the field lines at the satellite site, the smaller the $MT$ index. This definite relationship between $MT$ and field inclination denotes a systematic growth phase during which the field transition takes place in a regular way. If the transitions were random and irregular, such an anti-correlation result would not have been got. The outcome of this analysis supports the earlier finding in Sec. 4.5.2 that the specific entropy, a measure of disorder, remains constant for the growth phase.

$MT$ index at expansion and recovery phases could not reflect the field inclination as is evident from Figs. 5.8 and 5.9. During and after the expansion phase onset, the field transitions are too rapid and random. As explained in the previous section, such fast changes can be accommodated in $MT$ index only if the resolution of the index is much more. The resolution, of $MT$ in this analysis, is $\sim 2$ min., which is too small to represent rapid variations in instantaneous configuration during expansion and recovery phases.

5.6. Conclusion

Even though there are results in the literature showing good agreements between $MT$ and $I$, it was proved that the index fails in predicting
Fig. 5.10 $MT$ index vs. Field inclination at GOES 3 during the growth phase of 22 March 1979 substorm.
the field and its configuration in situations of rapid disturbances such as substorm expansion onset, expansion phase and recovery phase. The result demands the development of a still improved model to represent the instantaneous field configuration in the magnetotail at substorm onsets. Once such a model is developed, it might resolve the still unknown issues behind the real tail configuration during a magnetospheric substorm. In this context, this study forms the part of an effort to fully define the tail plasma dynamics and configuration during substorms.

$MT$ index, as seen, has its applications limited to periods with slow and systematic variations, of magnetospheric dynamics, like the substorm growth phase. The good agreement between $MT$ and tail field in such times and the disagreement between the two in other contexts bring out the fact that the magnetic field and its configuration in the tail are well controlled by slow and large-scale current components. Thus $MT$ index can be further used to study such current systems in the magnetosphere.

The limitations of the index are rather due to the fact that it is quite a new one and it can be expected that by increasing the temporal resolution and by applying necessary corrections to accommodate fast magnetospheric processes, $MT$ can emerge as a major tool in magnetospheric understandings.