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CHARACTERISTICS OF TRANSIENT MAGNETIC FIELD EVENTS IN THE DAYSIDE MAGNETOSPHERE

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Abstract: Transient magnetic field variations in the dayside magnetosphere, whose magnetic signatures resemble the flux transfer events (FTE's), are statistically investigated by using AMPTE/CCE magnetometer data during 1984–1986. These transient magnetic field events are observed in the $L=6.0$–9.4 and 0700–1600 magnetic local time (MLT) sector. It is found that the detection rate and the magnitude of magnetic field perturbation increase as the distance from the magnetopause decreases, which suggests that the transient magnetic field events are the phenomena near the magnetopause. In northern latitudes the radial component of the magnetic field shows a positive perturbation followed by a negative perturbation, while in southern latitudes the reversed sequence is seen. This tendency is the same as FTE's. Examination of the simultaneously obtained IMP-8 and ISEE-1 magnetic field data indicates that the transient magnetic field events occur mainly in association with southward orientation of the interplanetary magnetic field (IMF). This tendency is also the same as FTE's. These similarities in statistical characteristics suggest that the transient magnetic field events are caused by the same generation mechanism as FTE's. One of the interesting features revealed in this study is the MLT-dependence of the rotational polarity of the transverse magnetic field perturbation. The rotation is predominantly left-handed (with respect to the ambient magnetic field) in the forenoon sector, while it is right-handed in the afternoon sector. This suggests that the source of the magnetic field perturbation, presumably located near the magnetopause, moves azimuthally tailward.

1. Introduction

The processes governing the mass, momentum, and energy transfer from the solar wind to the magnetosphere and upper atmosphere are important topics of the magnetospheric research. The momentum and energy transferred across the magnetopause cause global convection in the magnetosphere, and supply the energy for magnetic substorms (directly or indirectly). The transfer mechanisms are mainly discussed in terms of two pictures: viscous interaction and reconnection. In the picture of the viscous interaction, magnetosheath plasma momentum is transferred to the magnetospheric plasma through viscous interaction at the magnetopause (AXFORD and HINES, 1961). Furthermore, due to viscous diffusion, the magnetosheath plasma itself enters into the magnetically closed magnetosphere to constitute the low latitude boundary layer (LLBL) plasma, and thereby carries momentum and energy into the magnetosphere (EASTMAN *et al.*, 1976). On the other hand in the picture of reconnection, the magnetosheath plasma (and also momentum and energy within it) enters into the magnetosphere by merging of interplanetary and magnetospheric magnetic field lines when the interplanetary magnetic field (IMF) has a southward component (DUNGEY, 1961).

The reconnection was regarded at first as a quasi-steady and large-scale process, so that it could cause global convection in the magnetosphere. PASCHMANN *et al.* (1979) and SONNERUP *et al.* (1981) reported the ISEE1 and 2 observations of such quasi-steady and large-scale reconnections in the dayside magnetosphere. However, other ISEE observations gave rise to a new type of reconnection model, *i.e.*, transient and small-scale reconnection. The magnetic field variations newly detected by ISEE1 and 2, first reported by RUSSELL and ELPHIC (1978), were characterized as follows: They have few minute time scales; in boundary normal coordinates, the component normal to the boundary designates bimodal perturbation, while the other components usually indicate one-sided pulse-like perturbations. These signatures were interpreted in terms of transient and patchy reconnection, *i.e.*, in terms of the encounter of single reconnected (open) small-scale magnetic flux tube (RUSSELL and ELPHIC, 1978). Thus, RUSSELL and ELPHIC (1978) termed these magnetic variations flux transfer events (FTE's). Further indication from the observation is that the FTE's are a very common feature near the magnetopause over a wide range of local times when the IMF is southerly directed, and that FTE's play significant role as a whole in the energy transfer

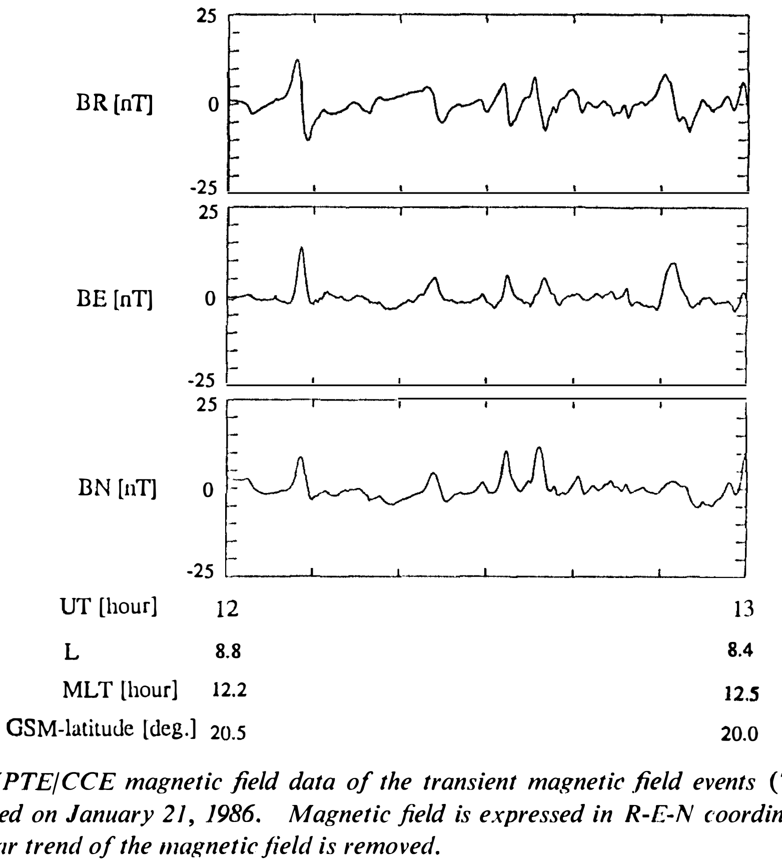

Fig. 1. AMPTE/CCE magnetic field data of the transient magnetic field events (TMFE's) observed on January 21, 1986. Magnetic field is expressed in R-E-N coordinates, and the linear trend of the magnetic field is removed.

process from solar wind to the magnetosphere (RUSSELL and ELPHIC, 1978; RIJNBEEK *et al.*, 1984).

In this report, we treat the impulsive magnetic variations whose magnetic signatures resemble FTE's but which were first detected fairly inside the dayside magnetopause, using data obtained by AMPTE/CCE (examples are shown in Fig. 1). PASCHMANN *et al.* (1982) and RIJNBEEK *et al.* (1984) have also identified the "magnetospheric FTE's", but their "magnetospheric FTE's" were mainly observed around $L=$ 10–12 just near the magnetopause-crossing. On the other hand, many of the events treated here were observed at $L=8$–9. Then, the purpose of this report is to clarify the statistical characteristics of these events (called 'transient magnetic field events' below) to compare them with the characteristics of FTE's.

2. Data Selection

AMPTE/CCE is a spacecraft launched on August 16, 1984. The spacecraft revolves nearly in the earth's geographical equatorial plane, and the apogee of the spacecraft is 8.8 R_E. The spacecraft revolves counterclockwise (seen from north pole) around the earth, and the orbital period is 15.6 h. The major axis of the orbit revolves clockwise (seen from north pole) around the earth, and the spacecraft covers all MLT (magnetic local time) sectors during ~485 days.

Magnetic field data obtained with CCE are used in this study, mainly in the form of microfiche plots, where the magnetic field data samples of 6.2 s are displayed in 1-hour plots. Effective resolution readable from microfiche is ~20 s for time and ~1 nT for magnetic field. The coordinates used to express magnetic field on the microfiche are *R-E-N* coordinates; *R* unit vector points from the earth center to the spacecraft, *E* unit vector is perpendicular to the dipole meridian plane of the spacecraft and points eastward, and *N* coordinate completes the (R, E, N) triad. Since the angle between the spacecraft orbit plane and the magnetic equatorial plane is less than ~28°, *N* axis is roughly parallel to the ambient dipole magnetic field. Furthermore, since the magnetopause is roughly perpendicular to the radial direction in low latitudes, the direction of *N* axis (normal to the magnetopause) in *L-M-N* coordinates (RUSSELL and ELPHIC, 1978) is roughly parallel to the direction of *R* axis in *R-E-N* coordinates.

The data used in this survey cover two periods from August 18, 1984 to February 3, 1985 and from October 25, 1985 to May 17, 1986, when the spacecraft apogee sweeps in the dayside region from dusk (1800 MLT) to dawn (0600 MLT) meridians.

The magnetic field data observed with IMP-8 and ISEE-1 spacecraft are available for the comparison of the AMPTE/CCE data with simultaneous IMF directions. The magnetic field of 1 min average is given in solar magnetospheric (GSM) coordinates.

We have sampled 305 transient magnetic field events (hereafter we will use the abbreviation TMFE for convenience) from the dayside data during 1984–1986 (as stated above) for the purpose of statistical analysis. Selection criteria are as follows:

* The radial distance of the spacecraft is greater than 6.0 R_E; this criterion is adopted because the magnitude of the average magnetic field changes rapidly at small distances.

* The R and N (in R-E-N coordinates) components show impulsive variations, with duration longer than 1 min. Here the "duration" is visually determined time difference between the start time and the end time of the entire perturbation.
* Amplitudes of R and N component perturbations are greater than 3 nT.
* A bimodal pulse in the R component and an one-sided pulse in the N component are clearly observed. Furthermore, the peak of the pulse in the N component appears roughly at the center between the maximum and minimum of pulse in the R component.

Examples of the sampled TMFE's are presented in Fig. 1. Bimodal pulses in R component and simultaneous one-sided pulses in N and E components are clearly seen. Although not shown in the figure, these events were followed by magnetopause-crossing at ~1321 UT. However, many of the sampled 305 TMFE's did not accompany magnetopause-crossings before or after the events. Note that FTE's have always been observed near the magnetopause-crossing, which has made clear that the FTE's are the phenomena around the magnetopause.

3. Spatial Distribution

Figure 2 shows the locations of the 305 TMFE's in MLT and GSM-latitude. There exists a bias in data distribution; the data are distributed in an arc-like form, and in the 09–12 MLT sector most events occurred in northern latitudes. The arc-like distribution comes from the fact that the period of survey was mainly in the northern winter season. Since the orbital plane is nearly in the geographical equatorial plane (difference is within 4.8°), the orbit is located in northern GSM-latitudes in northern winter and located in southern GSM-latitudes in northern summer.

Figures 3 to 5 show dependences of TMFE occurrence upon three position parameters: GSM-latitude, MLT, and L value. Figure 3 is a histogram of the occurrence against GSM-latitude. The bias in the occurrence is reduced; the occurrence is

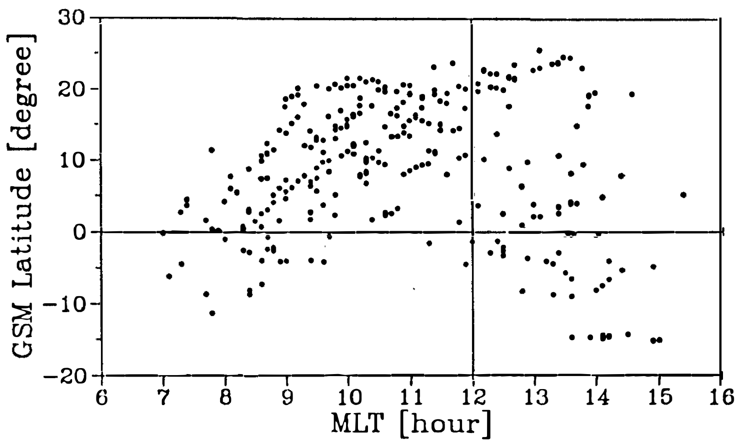

Fig. 2. Locations of 305 TMFE's with regard to GSM-latitude and MLT. The locations are biased toward northern latitudes. This bias is not a real tendency but an effect of the nature of CCE orbit.

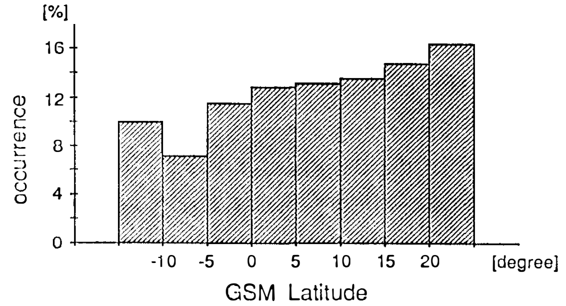

Fig. 3. Histogram of the TMFE occurrence as a function of GSM-latitude. The occurrence (vertical axis) is normalized by the orbital coverage over GSM-latitude.

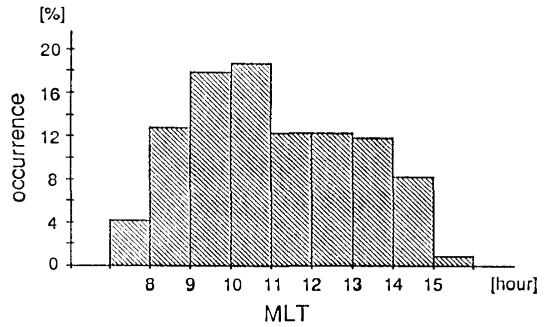

Fig. 4. Histogram of the TMFE occurrence as a function of MLT. The occurrence is normalized as in case of Fig. 3.

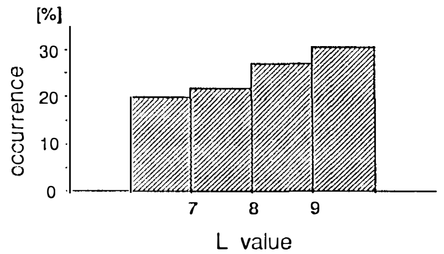

Fig. 5. Histogram of the TMFE occurrence as a function of L value. The occurrence is normalized as in case of Fig. 3.

normalized by the orbital coverage distribution in GSM-latitude. It is noted a tendency in Fig. 3 that the occurrence increases with increasing GSM-latitude in northern latitudes. In southern latitudes, the GSM-latitude-dependence is uncertain because of narrower coverage of GSM-latitude. If we assume that in southern latitudes the occurrence is also higher at higher latitudes, this GSM-latitude-dependence is the same as that of FTE's (BERCHEM and RUSSELL, 1984; RIJNBEEK *et al.*, 1984).

Figure 4 is a histogram of TMFE occurrence against MLT. The occurrence is normalized as in case of Fig. 3. The histogram indicates a forenoon-afternoon asymmetry of the occurrence; it is more frequent in the forenoon sector than in the afternoon sector.

The histogram of the occurrence against L is shown in Fig. 5. The occurrence is also normalized. The histogram shows that the occurrence increases with increasing L.

We present below possible interpretations of the observed GSM-latitude-, MLT-, and L-dependences of the occurrence.

Since the observed GSM-latitude-dependence of the occurrence of TMFE's (Fig. 3) is the same as that of FTE's, the same viewpoint of explanation as in the case of FTE's is applicable to the TMFE's, *i.e.*, explicable in terms of reconnection. That is,

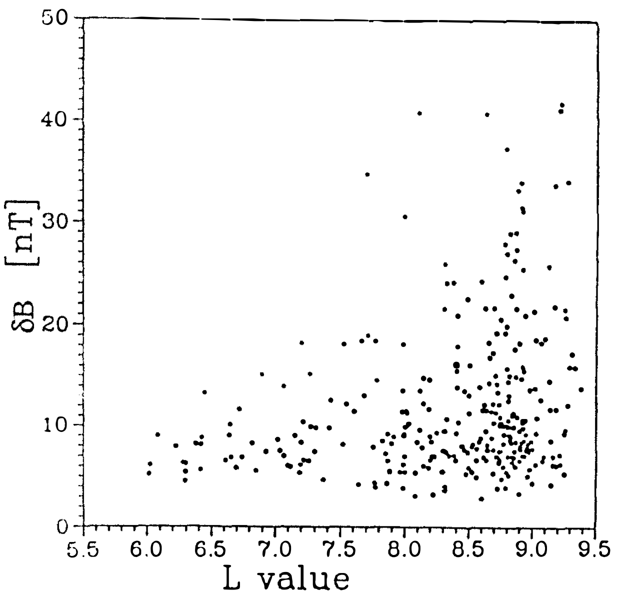

Fig. 6. Plot of the magnitude of the magnetic field perturbation, δB, versus L value. The events with large δB tend to be detected at large L region.

reconnection is active near the equator, thus the TMFE's are generated near the equator and move toward higher latitudes as they grow. Therefore, in low latitudes the events have small amplitudes, which cause a small detection rate.

The asymmetry in MLT-dependence (the occurrence is more frequent in the forenoon sector than in the afternoon sector) may be ascribed to the angle of IMF onto the magnetosheath. From Parker's spiral structure in the IMF, projected vector of IMF on X-Y plane (in GSM coordinates) is nearly perpendicular to the surface of the magnetosheath around 9000–1100 MLT sector. In this sector, particles are highly accelerated through quasi-parallel shock (CROOKER *et al.*, 1981), and this feature may affect the phenomena occurring near the magnetopause of this sector.

The characteristics of the L-dependence is that the occurrence increases as L increases. Since the geocentric distance of the magnetopause usually ranges from 9 to 13 R_E, even though the magnetopause moves inward or outward frequently, it is reasonable that as L (the position of the spacecraft) increases, the distance between the spacecraft and the magnetopause decreases. Then, the observed L-dependence can be interpreted as follows: the occurrence increases as the distance between the spacecraft and the magnetopause decreases. This suggests that the events occur frequently in the vicinity of the magnetopause.

In addition to Fig. 5, we present Fig. 6 as another support for the occurrence frequency near the magnetopause. This figure is a plot of the magnitude of the magnetic field perturbation, δB, versus L value, showing that large δB tends to be detected at large L. In other words, the events with large δB tend to be detected in the region closer to the magnetopause than the events with small δB. This also suggests that the TMFE's are originated at or near the magnetopause.

4. Perturbation Mode and Polarity

The bimodal radial magnetic field perturbation is one of the interesting features

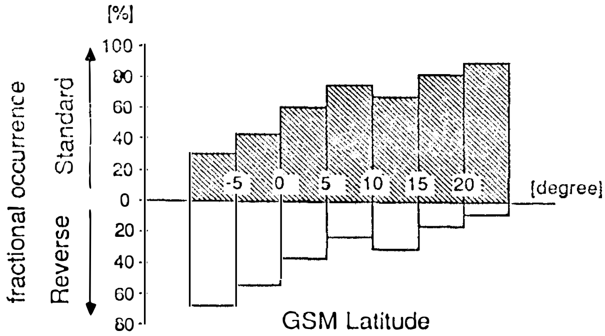

Fig. 7. Histogram of the fractional occurrence of the standard and reverse events as a function of GSM-latitude. In each of 5° GSM-latitude ranges, the number of the standard and reverse events are summed up and normalized to unity. There is a clear GSM-latitude-dependence of the ratio of standard/reverse events. The rate of the standard events decreases with decreasing GSM-latitudes.

of TMFE's. Following RIJNBEEK *et al.* (1984), we have classified the events into the standard type (positive followed by negative radial component) and the reverse type (negative followed by positive radial component).

The GSM-latitude-dependence of the occurrence of standard and reverse events are plotted in Fig. 7. Here the number of the standard and reverse events are counted for each of 5° GSM-latitude ranges. Then, in each of the 5° intervals the number of both types are summed up and normalized to unity. The figure indicates that in northern latitudes the standard events occur more frequently. There are less number of events in southern latitudes, which would give rise to an uncertainty in the standard/reverse ratio. Nevertheless, a clear systematic increase in the ratio of the reverse events with decreasing GSM-latitude strongly supports the predominance of reverse events in southern latitudes.

Since this GSM-latitude-dependence of standard/reverse ratio of the TMFE's is the same as that of FTE's, the same viewpoint of explanation as in case of FTE's is applicable to the TMFE's, *i.e.*, explicable in terms of poleward motion of the magnetic flux tube along the magnetopause (BERCHEM and RUSSELL, 1984; RIJNBEEK *et al.*, 1984). Magnetic field surrounding the flux tube is distorted, and the distorted magnetospheric magnetic field has radial outward component in the north of the tube and radial inward component in the south of the tube. Thus, if the flux tube moves northward past an observer, the radial component points first outward as the tube approaches and then inward as it leaves (standard type). On the other hand, southward motion of the flux tube causes inward followed by outward radial perturbation (reverse type). Then, the observed ratios of standard and reverse events are interpreted in terms of primarily northward flux tube motion in northern latitudes and southward motion in southern latitudes; this suggests that the reconnection is frequent near the equator and the generated flux tubes move toward higher latitudes.

The second feature of magnetic field perturbation is a MLT-dependence of the rotational polarity of the transverse perturbation. The polarity is defined as "right-handed" or "left-handed" according to whether the transverse perturbation rotates in a right-handed sense or left-handed sense with respect to the ambient magnetic field

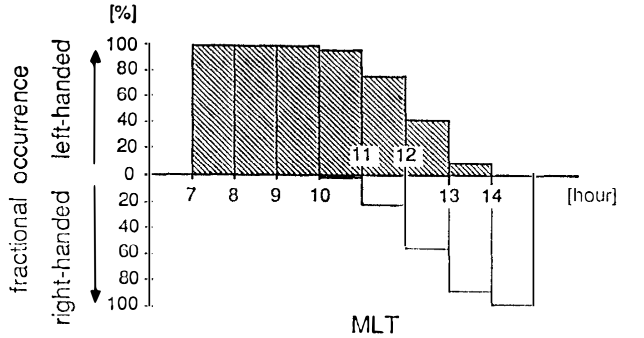

Fig. 8. Histogram of the fractional occurrence of right-handed and left-handed events as a function of MLT. For each MLT, the number of right-handed and left-handed polarity events are summed up and normalized to unity. There is a clear reverse of polarity around noon.

(for example, polarities of all events in Fig. 1 are right-handed).

Figure 8 shows the MLT-dependence of the rotational polarity. Here, the events are classified into 1-hour MLT intervals, and then the normalized occurrence probability is calculated for each MLT interval. The figure shows a clear reversal in the rotational polarity around noon; left-handed in the forenoon sector and right-handed in the afternoon sector. This polarity variation has not been reported for the FTE-type transient events, and strongly suggests the azimuthal tailward motion of the magnetic structure.

Here we demonstrate how this azimuthal tailward motion is deduced, using a simple line current tube model. The existence of field-aligned currents in FTE's is inferred from observations (COWLEY, 1982, and references therein). Then, we assume that the TMFE's has a magnetic flux tube structure and that the transverse components of the magnetic field perturbation (δB_R, δB_E in R-E-N coordinates) are caused by the field-aligned currents in the flux tube. The flux tube is assumed to be located near the magnetopause, and to move along the magnetopause (this assumption means that all the TMFE's are located outside the position of CCE). Tube orientation is assumed to have north-south component. The speed of the tube motion is expected to be much faster than the speed of the spacecraft displacement. Figure 9 illustrates the expected rotational polarity of the transverse perturbation as the tube moves azimuthally past the spacecraft; westward-moving current tube causes "left-handed" polarity regardless of whether the current-orientation is northward or southward; eastward-moving current tube causes "right-handed" polarity regardless of whether the current-orientation is northward or southward. Then, the observed distributions of "left-handed" and "right-handed" polarities are interpreted in terms of primarily westward current tube motion in the forenoon sector and eastward in the afternoon sector, *i.e.*, azimuthal tailward motion. Note that this current tube model is the most simplified one to demonstrate azimuthal tailward motion, and does not include information about actual current system. However, as long as the tube moves azimuthally tailward, any current system in the flux tube would cause the observed rotational polarity of the transverse perturbation, because the current-orientation does not affect the rotational polarity. In this way, the MLT-dependence of the rotational polarity can be explained

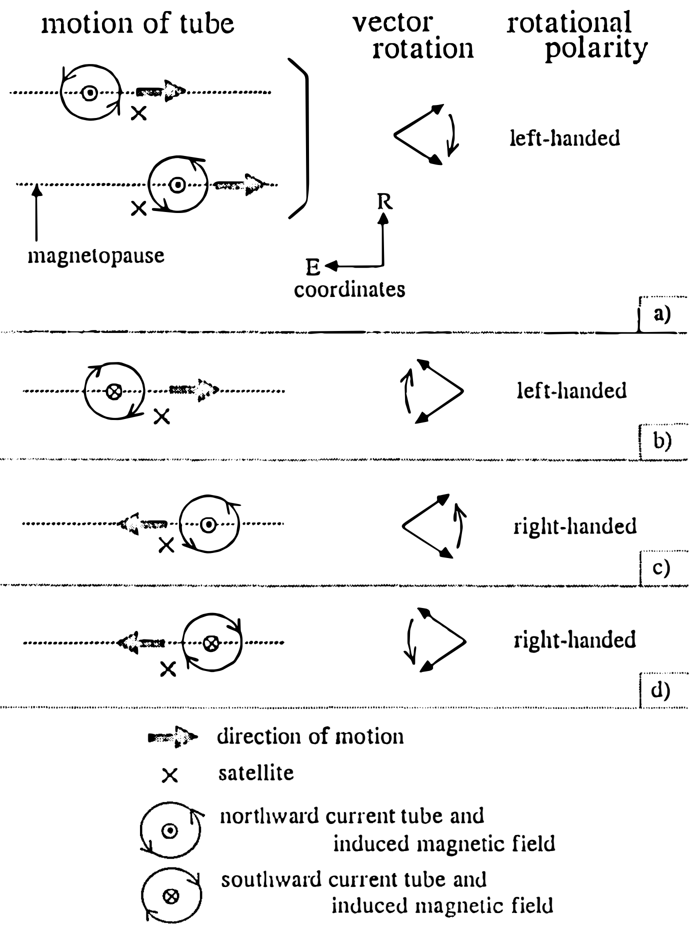

Fig. 9. Simple current tube model for transverse magnetic field perturbation. The upward direction on the paper corresponds to N direction in R-E-N coordinates. The left direction on the paper corresponds to E direction in R-E-N coordinates. The axes of coordinates are depicted in Fig. 9a. Left-side pictures illustrate the tubes seen from north, the orientation of current in the tube, and the direction of motion of the tube. Right-side pictures illustrate the corresponding rotations of magnetic field perturbation at observation site (at the position of satellite) which is inside the magnetopause. Straight arrows indicate the magnetic field perturbations, while arc-shaped arrows indicate the direction of time variations of the magnetic field perturbations. Clockwise and counter-clockwise arc-shaped arrows correspond respectively to left-handed and right-handed rotations.

in terms of the azimuthal tailward motion of the flux tube.

5. IMF-Dependence of TMFE Occurrence

We have also examined the relationship between the interplanetary magnetic field (IMF) condition and the TMFE's. Among all the transient magnetic field events in our database, IMF (1 min value) data from IMP-8 and ISEE-1 were available (satisfying the condition that the spacecraft was at $X_{GSM}>15\ R_E$) for 29 events. For these 29 events, IMF $B_{Z(GSM)}$ were surveyed for the period of ± 30 min from event times (convection time lag was approximately removed by assuming a solar wind velocity of 450 km/s). Then, events were identified for which IMF B_Z remained either northward or southward during the 1-hour interval. As a result, we found 6 events, and all of the 6 events showed negative B_Z. Despite the small number of data, this tendency is also the same as that for FTE's (BERCHEM and RUSSELL, 1984; RIJNBEEK *et al.*, 1984), and readily interpreted in terms of reconnection because reconnection is thought to take place when the geomagnetic field and IMF are antiparallel.

6. Discussion

In this paper we have made a statistical analysis of the TMFE's, using AMPTE/CCE magnetic field data. The TMFE is similar to FTE in that the radial magnetic variation exhibits a bimodal perturbation, while other components exhibit one-sided pulse perturbations. However, the region where the TMFE's are observed is different from that of FTE's; the TMFE's are observed at L=6.0–9.4, while previously reported FTE's are observed mainly in close proximity to the magnetopause, at L=10–12. Further, many of the TMFE's are observed without magnetopause-crossing before or after them. Thus, there is no direct proof that the TMFE's are observed near the magnetopause. Nevertheless, increasing detection rate and increasing magnitude of magnetic field perturbation with decrease in the distance from the magnetopause suggest that the TMFE's are the phenomena in the vicinity of the magnetopause. Moreover, large occurrence rate for southward IMF, large occurrence rate at high latitudes, and frequent appearance of standard events in northern latitudes and reverse events in southern latitudes, are all the same tendencies as those for FTE's. These results suggest that the TMFE's come from the same generation mechanism as FTE's. Then, detection of the TMFE's at small-L region indicates a great inward motion of the magnetopause, and thus high geomagnetic activity.

The MLT-dependence of the rotational polarity of the transverse magnetic field perturbation of the TMFE's strongly suggests a tailward motion of these structures, dawnward in the forenoon sector and duskward in the afternoon sector. Then it is expected that the FTE structures also move tailward, which would also cause MLT-dependence of the rotational polarity for FTE's. On the other hand, the northward or southward motion also exists, as is suggested from the latitude-dependence of the standard or reverse events. Thus the motion of the TMFE's (and possibly of FTE's) are tailward in both azimuthal and north-south direction.

Observed great occurrence rate for southward IMF particularly profits the reconnection-type generation mechanism. However, the other possibilities, such as possibility of solar wind dynamic pressure driven pulses (SIBECK *et al.*, 1989), still exist. Since our event selection criteria are based only on magnetic field signatures, there is a possibility that the events caused by different mechanisms are included in the sampled events. In order to distinguish the difference in generation mechanism, particle and plasma data would be essential. Aside from it, the IMF-dependence itself should be tested with more IMF data.

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