Neutral Line in the Magnetotail*

By

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1. INTRODUCTION

In the open model of the magnetosphere, it is thought that magnetic field lines are transported from the dayside of the magnetosphere to the magnetotail as a consequence of the reconnection process operating on the dayside magnetopause (Dungey, 1963). In order that the flux content of the tail does not grow indefinitely it is required that the reconnection process operates also in the magnetotail and allows the field lines to return to the dayside. It has been suggested that this nightside reconnection does not proceed continuously but occurs explosively giving rise to the major magnetospheric phenomenon known as substorm (Dungey, 1966; Atkinson, 1966; Axford, 1967).

Recently we have carried out a synoptic survey for the magnetotail neutral line and the associated plasma phenomena during substorms in an attempt to provide the observational basis for the nightside reconnection process. The results and implications of this analysis, which has been carried out in collaboration with Mr. N. Nagayama and Dr. E. W. Hones, Jr., are briefly summarized in this note.

2. NEUTRAL-LINE FORMATION DURING SUBSTORMS

The ideal way of detecting the neutral line is to cover the magnetotail by a dense network of satellites equipped with magnetic probes. This being practically impossible, we have chosen to combine the observations made at different locations for different substorms on the assumption that the tail behaviour is essentially the same for every substorm. In Fig. 1 the tail magnetic field records for two instances of substorms (left and right) are examined. On the top is the projection of the satellite position to the xy plane. (Throughout this paper the solar magnetospheric coordinate system is employed.) Data from two satellites are available for each instance, and F and D are abbreviations for the satellite designations IMP-F (Explorer 34) and AIMP-D (Explorer 33). In the next panel ~ 3 min averages of the B_z (north-south) component of the magnetic field obtained by

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FIG. 1. Tail magnetic field records (middle panel) obtained during substorms at $x \simeq -10 R_e$ (left) and $x \simeq -30 R_e$ (right). Observing sites are noted in the top panel in the unit of R_e .

these satellites are shown. Records in the last panel are tracings of ground magnetograms from equatorial (top) and auroral-zone (bottom) stations that happened to be located near the geomagnetic midnight meridian.

In the ground magnetograms the onset of the expansion phase of the substorm is recognized as onsets of a low-latitude positive bay and of an auroral-zone negative bay (c.f., Iijima and Nagata, 1972). The vertical lines in the figure are drawn with reference to the onset time noted in the equatorial record which is subject less to local modifications. In the February 21 event (left) both satellites are located at $x \simeq -10 R_e$ and they have recorded the increase in B_z at the expansion phase onset. On the other hand, in the March 29 event (right) where both satellites are around the $x \simeq -25$ to $-30 R_e$ range the decrease in B_z is observed at the expansion phase onset. In particular, at IMP-F located at $y \simeq 11 R_e$ B_z turns clearly southward about 10 min after the expansion-phase onset time determined by the ground data. Thus, the magnetotail B_z variation observed in association with the substorm expansion phase changes sign somewhere between $x \simeq -10$ and $-25 R_e$.

This tendency is confirmed for a greater number of cases in Nishida and Nagayama (1973a), and the sequence of magnetic-field structural change in the near-

FIG. 2. Left: Structural change of the magnetotail during substorms. Time is counted from the onset time of the low-latitude positive bay in the near-midnight meridian. The shading expresses the plasma sheet location. Right: Difference in the magnetic field distribution between successive phases of substorms (Nishida and Nagayama, 1973a).

midnight meridian is shown on left hand side of Fig. 2. The top is the familiar quiet-time field structure observed about 100 min before the expansion-phase onset. The second is the field structure observed toward the end of the growth phase, and it is characterized by the severe stretching of low-latitude field lines in the $x \simeq -10$ to $-20 R_e$ range and also by the increased flaring angle (with respect to the xy plane) and magnitude of the high-latitude magnetic field (c.f., McPherron, 1972). Then in the expansion phase the field structure turns to the one shown in the bottom which involves a neutral line located in the near-tail region.

Unfortunately, the low-latitude range at $x \simeq -10$ to $-25 R_e$ where the neutral line is expected to be located is not adequately covered by the available satellite magnetometer records, but the inferences made from the plasma analysis (Hones et al., 1973) locate the neutral line at $x \simeq -15 R_e$. The time delay of about 10 min noted in the March 29 event between the expansion phase onset on the ground and the southward field turning at IMP-F would be attributable, at least in part, to the X -type field configuration to spread from $x \simeq -15 R_e$ to the IMP-F location of $x \simeq -31 R_e$. As exemplified by the March 29 event the B_z decrease at $x \lesssim -25 R_e$ is observed in a wide range of y (viz., local time) but a clear turning of B_z to the southward polarity is seen in a limited range of $|y| \lesssim 10$ to $15 R_e$. The

neutral line seems to have a length of 20 to 30 R_e and does not appear to reach the magnetopause.

The right hand side of Fig. 2 shows the difference of the magnetic field distributions between the growth phase and the quiet state (above) and between the expansion phase and the growth phase (below). It is seen that during the growth phase the intensification of the currents flowing in the plasma sheet and on the magnetotail surface in the $x \gtrsim -30 R_e$ range is principally responsible for the tail field distortion. When the expansion phase sets in these currents are sharply reduced, and the tail current around the earthward end of the plasma sheet drops below the quiet-time level, resulting in the neutral-line formation in the near-tail region. The duration of the field configuration with the neutral line usually ranges from 0.5 to 1 h.

3. ASSOCIATED PLASMA-SHEET BEHAVIOUR

The plasma sheet responds sensitively to the formation of the neutral line. This is illustrated in Fig. 3 where a record of the tail magnetic field obtained by IMP-F is compared with the simultaneous observation of the low-energy (63 eV to 18.5 keV) electron pressure by Vela 4A (top panel). The satellite coordinate at 1000 UT is given in the unit of R_e after the satellite code. (In this figure only, z is replaced by dz which is the distance from the neutral-sheet (where B_x changes sign) position estimated by the Russell-Brody (1967) formula.) Both satellites are in the neighbourhood of the neutral sheet. The bottom panel presents the ground magnetograms from low-latitude (above) and auroral-zone (below) stations around midnight. Local times given after the station code are also for 1000 UT.

During the interval of Fig. 3 the low-latitude tail field enters the southward range three times indicating the repeated formation of the neutral line earthward of the satellite position. Vertical lines are drawn at the timings of these southward turnings. The ground records testify that each of these are associated with the expansion phase of a substorm. According to the plasma data the latter two of these events are associated with clear depressions in the electron pressure lasting roughly throughout the duration of the southward tail field. The same correlation as the above has been noted in several other occasions where simultaneous field and plasma observations at low $|dz|$ are available, and it can be concluded that the rapid thinning of the plasma sheet occurs beyond the neutral line (Nishida and Hones, 1974). When the plasma reappears after the depression it tends to be rich in the energetic-electron ($\gtrsim 36$ keV) component, and occasionally a burst of energetic electrons is observed in association with the southward turning of the low-latitude tail field.

As for the first event in Fig. 3 the electron pressure does not drop but the energetic-electron flux has decreased at the corresponding timing. Since the distance $|dz|$ of Vela 4A is steadily increasing during this interval from $1.3 R_e$

FIG. 3. Comparison of a tail field record (top panel, above) with a simultaneous electron pressure data (top panel, below) during substorms (Nishida and Hones, 1974).

(at 0800) to $2.4 R_e$ (at 1100), this event may be taken to demonstrate that while the plasma sheet thins it does not entirely disappear. To make the picture of the plasma-sheet behaviour complete it should also be noted that in high latitudes of the tail the plasma-sheet thinning is observed to start prior to the expansion phase onset (Hones et al., 1971), and that the inward motion of the earthward boundary of the plasma-sheet is observed at the geosynchronous orbit ($6.6 R_e$) for ~ 1 h before the expansion phase (Mende et al., 1972), viz. before the formation of the neutral line in the near-tail region. The plasma-sheet structure in Fig. 2 is drawn taking these points into account.

By way of passing it is noted that two more substorm expansion phases are recognized in Fig. 3 to start around 0750 and 1203 but the southward turning of the field is not detected by IMP-F. This is probably because the satellite is brought to the high-latitude region of the tail due to the irregular flapping or tipping motion of the tail. Also, the observation is made at $y \simeq -12 R_e$ where the effect of the neutral line is not always clear.

4. DEPENDENCE ON THE INTERPLANETARY CONDITION

Since the nightside reconnection is considered to be the consequence of the flux build-up in the magnetotail, the occurrence of the tail neutral line is expected to depend on the interplanetary condition that is thought to govern the dayside reconnection rate. The relevant interplanetary parameter is the north-south component B_z of the interplanetary magnetic field (Dungey, 1963).

Figure 4 shows the tail and ground field response for a particularly simple case in which the interplanetary field develops a large ($\sim 8 \gamma$) southward component after an interval of $|B_z| \lesssim 2 \gamma$ lasting for about 1 h (left, top). In this instance the solar wind speed is about 330 km/sec and the transit time correction (estimated by dividing the AIMP-D x coordinate by the solar wind speed) is roughly 11 min. Following the southward movement of the interplanetary magnetic field, B_z in the low-latitude tail enters the southward range several times but the most persisting and most intense southward tail field is seen to start about 100 min after the arrival of the southward interplanetary field (left, middle). In the rest of the records which are ground magnetograms, it can be seen that the beginning of the above interval of the southward tail field (indicated by a vertical line) corresponds to the intensification of the disturbance field that is identifiable as the onset of the substorm expansion phase.

FIG. 4. Response of the tail field (left, middle) and the ground field at nightside low latitude (left, bottom) and at nightside auroral zone (right) to a southward movement of the interplanetary magnetic field (left, top). Satellite positions (solar magnetospheric) and station local times are given for the expansion phase onset time.

Thus the present sample suggests that the principal reconnection process on the night side of the magnetosphere starts to operate 1~2 h after the onset (or, intensification) of the dayside reconnection. During this 1~2 h interval the flux build-up is supposed to be proceeding in the lobe region of the tail, and indeed the lobe field has been seen to intensify for 1~2 h following well-defined southward movements in the interplanetary magnetic field (e.g. McPherron, 1972; Nishida and Nagayama, 1973b). The “growth phase” duration of this magnitude has also been deduced from particle and field observations at various locations in the magnetosphere during isolated substorm events (e.g. Mende et al., 1972). Although brief intervals of the southward tail field noted in Fig. 4 prior to the expansion phase might be taken to be an indication of the occasional formation of neutral lines, such premature neutral lines obviously do not develop to cause a major release of energy from the magnetotail. (These brief southward tail fields may actually be due to flapping or tipping motions of the tail and do not necessarily reflect the neutral-line formation.)

In the sample presented above the interplanetary field continues to have a southward polarity for several hours until ~0100 of the next day (February 28), but notably the southward tail field does not last throughout that interval; about 45 min after its southward turning the tail field polarity returns to northward, and correspondingly the ground magnetic activity in the near-midnight region begins to subside. This suggests that the nightside reconnection is not a continuous process, even when the interplanetary magnetic condition indicates the persistence of the dayside reconnection. Another case in favour of this inference is the sample of Fig. 3; this sample corresponds to a large and relatively steady interplanetary field with a southward polarity ($B_z \simeq -12\gamma$), but the southward field in the low-latitude tail is observed to occur only intermittently every ~1 h with a duration of ~0.5 h. Thus it seems that the nightside reconnection stops to operate as soon as the magnetic flux content of the magnetotail is reduced to some threshold, and is not resumed until the tail flux content becomes significantly larger than that threshold value.

The next sample, Fig. 5, shows the response of ground and tail fields to interplanetary B_z fluctuations (top panel, second record) with a time scale of about 1 h. In the interval concerned the dynamic pressure $P_d = \rho v^2$ of the solar wind (top panel, first record) is kept at a relatively steady level. The solar wind speed is about 400 km/sec and the transit time correction is about 14 min. These B_z fluctuations are reflected in the ground magnetograms from polar-cap (Resolute Bay) and dayside equatorial (Huancayo) stations (reproduced in the second panel) as DP 2 fluctuations. The time delay between interplanetary B_z fluctuations (with southward taken as positive) and the ground DP 2 (with H increase at the dayside equator taken as positive) is about 15 min after the transit time correction. On the other hand, in the magnetogram records from nightside auroral-zone (College) and low-latitude (Honolulu) stations (in the third panel), DP 2 is masked by the substorm expansion phase (DP 1) whose onset is associated with the formation of the neutral line in the near-tail region as manifested by the

FIG. 5. Occurrence of DP 2 (second panel) and substorm expansion phase (third and fourth panels) in the interval of fluctuating interplanetary magnetic field (top panel). At 1000, AIMP-D is monitoring the interplanetary space at $(56, -31, -36) R_e$ and IMP-F is in the low-latitude tail at $(-33, -2, -2) R_e$.
 * The unit of $\sqrt{P_d}$ is $(10^{-4} \text{ dyn/cm}^2)^{1/2}$.

southward turning of the low-latitude tail field observed by IMP-F (last panel). In this way dayside and nightside reconnection processes are reflected in the ground magnetic field as different types of disturbance fields.

5. CONCLUDING REMARKS

We have seen that the formation of the neutral line in the near-tail region is due to the severe weakening or disruption of the cross-tail current flowing through the earthward end of the plasma sheet. In the stage that immediately precedes the neutral-line formation the nightside field lines are stretched to the tail-like configuration even at a distance as close to the earth as $x \simeq -10 R_e$, and the cross-tail

current is highly intensified in the region where it is soon to disappear. Hence it would be natural to consider that the instability of this current flow is involved, and the search for plasma waves that have grown out of the instability is of much interest. Scarf and Fredricks (1972) have reported a couple of instances in which the growth of the electric field oscillations in the ~ 1 kHz range is observed by OGO 5 at the distance of $8\sim 10 R_e$ following the onset of the substorm expansion phase. In order to pursue this point we have asked Dr. Scarf to look at the OGO 5 VLF electric field record at the time of twelve more expansion-phase onsets included in Figs. 2 and 6 of Nishida and Nagayama (1973a). According to Dr. Scarf, however, the result of the examination is rather negative; of the 12 cases examined only 2 are found to accompany the VLF electric field excitation of any kind, and he has pointed out that the condition $T_e \ll T_i$ that prevails in the plasma sheet is not favourable for the growth of electrostatic waves. In any event, the observing sites of OGO 5 are probably still $\sim 5 R_e$ earthward of the neutral-line position, and the advent of the vehicle which can make *in situ* observation of the neutral-line characteristics is highly desirable.

As the formation of the neutral-line is associated with the intensification of the electrojet flowing in the auroral-zone ionosphere it may be thought that the current that has disappeared from the tail is transposed to the ionosphere. Such a model, however, seems to have some difficulties. First, the auroral electrojet persists after the disappearance of the neutral line from the near-tail region. All the samples presented in this note show that the return of the low-latitude tail field from southward to the northward range is roughly coincident with the peak of the auroral-zone negative bay, but not the end of it. Second, while the intensification of the westward auroral electrojet does not seem to occur simultaneously all over the nightside ionosphere, the magnetotail collapse tends to occur nearly simultaneously all across the tail. Specifically, the negative bay onsets in the evening sector tends to show a delay that reflects the transit time of the westward travelling surge, but the B_z increase observed by OGO 5 on the earthward side of the neutral line is within ~ 5 min of the expansion-phase onset time registered in the near-midnight region even when OGO 5 is in the 19 LT (solar magnetospheric) meridian (Nishida and Nagayama, 1973a). Thus the auroral electrojet is not likely to be the mere transposition of the cross tail current. During the reconnection the tail field energy is converted to the kinetic energy of the tail plasma and the heated plasma is convected to the nightside inner magnetosphere. The energy of such plasma would act to create a variety of disturbances observed on the ground as the substorm phenomena.

Finally, there have been suggestions of the nightside reconnection process that does not involve the neutral-line in the near-tail region. Examples are the one that can proceed under $B_z = 0$ (Dungey, 1972) and the other which is associated with a neutral line located at a greater distance (c.f. Hones et al., 1973). According to our analysis these processes are not likely to be the principal agent of the substorm, but a more detailed analysis is needed to assess the relevance of these suggestions to the overall magnetospheric process.

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