Magnetotail Changes in Relation to the Solar Wind Magnetic Field and Magnetospheric Substorms

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Substorm activity is known to be associated with changes in the solar wind parameters and the magnetotail configuration. In this paper we investigate whether the magnetotail changes occur only as a consequence of substorms or also as a direct consequence of changes in the solar wind parameters. Using data from several satellites (Ogo 5, ATS 1, Imp 4, Explorer 33 and 35) and 17 ground magnetic observatories, we conclude that the tail responds to both changes in the north-south orientation of the interplanetary field and substorm activity. Specifically, we show the following. (1) A change from a northward to a southward interplanetary field causes a slow increase of the field to be recorded by a satellite within the lobe of the tail, and a thinning of the plasma sheet. (2) A change from a southward to a northward interplanetary field causes the plasma sheet to expand. In contrast, it seems that in the inner magnetosphere the distortion of the magnetic field due to a period of southward interplanetary field is not relieved by an interval of northward field but only through the occurrence of a substorm expansion. (3) A substorm expansion causes a slow decrease of the field within the lobe of the tail and an expansion of the plasma sheet.

Many attempts have been made recently to understand the cause of magnetospheric substorms. Because of the major role it plays in the various theories presently available, the magnetotail region has been particularly well investigated by a number of experimenters. Particle observations have shown that in the tail at 17 $R_{\oplus}$ from the earth 45-kev electrons in the plasma sheet disappear before and reappear coincident with or after the sharp maximum of the bay in the auroral zone [Hones et al., 1967]. Hones [1969] has clearly demonstrated that this signature is produced by a thinning of the plasma sheet in the initial phase of substorms and then a subsequent expansion.

During the thinning, the border of the plasma sheet has been shown in one occasion to move toward the neutral sheet at a velocity of 6 km/sec. In contrast, the expansion is characterized by a velocity away from the neutral sheet ranging from 5 to 20 km/sec [Hones et al., 1970, Akasofu et al., 1970]. Magnetic field observations between 10 and 40 $R_{\oplus}$ behind the earth have shown two main kinds of variation of the tail magnetic field, namely, slow increase or decrease of the field at a rate of several gammas per minute [Anderson and Ness, 1966; Heppner et al., 1967; Fairfield and Ness, 1970; Camidge and Rostoker, 1970; Brody and Holzer, 1970; Russell et al., 1971]. The typical substorm signature in the tail is a slow increase of the field followed by a rapid decrease. This sharp decrease in the field is generally considered to be due to a spatial phenomenon, the expansion of the plasma sheet observed by Hones [1969], Hones et al. [1970], and Akasofu et al. [1970]. Since the time of this rapid decrease can be accurately measured, many authors have tried to relate it to the best-defined feature of the auroral substorm, the onset of the expansion phase. The results vary considerably from one author to another: the field decrease can be seen to coincide roughly with the beginning of the expansion phase of the substorm [Camidge and Rostoker, 1970; Rostoker, 1970] or to occur within a well-defined delay (14 to 15 min as observed by Heppner et al. [1967]). By study-
ing about 20 substorms when the Ogo A satellite was in the tail, Brody and Holzer [1970] found that the field decrease occurs on the average 54 min after the onset of the expansion of the auroral substorm. The reason for these divergent results is that, as will be shown in this paper, some of the rapid decreases of the tail field are not related to substorms. In the present study we have separated the rapid and slow variations of the tail field and tried to find which of them, if any, is directly related to substorms.

Observations of changes in the tail magnetic field were provided by the published data from Imp 4 [Fairfield and Ness, 1970]. These authors established the association of some changes in the tail field with substorm activity using the AE index. We have attempted to extend this work by a careful timing relative to the expansion phase of substorms and by checking the solar wind parameters as a possible origin of these changes. The solar wind plasma parameters were obtained by the MIT experiment on board Explorer 33 and 35 (Dr. Binsack); the interplanetary magnetic field parameters were obtained with the NASA Ames magnetometer on board these two satellites (Dr. Sonett) and were provided by the National Space Science Data Center. The occurrence of substorms in the inner magnetosphere was determined from the UCLA magnetometer on board the synchronous satellite ATS I and various ground magnetograms (obtained from World Data Center A for Geomagnetism.)

These data show that the tail can respond directly to the solar wind in the following ways. (a) When the interplanetary field turns southward the magnetic field increases in the main lobe of the tail and the plasma sheet thins. (b) When the interplanetary field turns northward the plasma sheet expands. These variations, due only to the solar wind, must be combined with those due to substorm expansions: decrease of the magnetic field in the main lobe and expansion of the plasma sheet.

We shall present three examples illustrating the tail response in each of the above cases. The first, on February 13, 1963, slow changes in tail field. We chose this day because the observations made by Imp 4 in the tail were relatively free of the influence of the rapid expansion of the plasma sheet (except after 1800 UT) and this allows us to analyze the slow increases and decreases of the tail field. Figure 1 presents the solar wind data from Explorer 35, namely, the hourly averages of the streaming energy density $pV^2$ (only protons are supposed to be present), the thermal energy density $NkT$, as well as the variation of the 80-sec averages of the angle $\alpha$ between the interplanetary magnetic field and the ecliptic plane. The lower part of the figure reproduced from Fairfield and Ness [1970] presents the tail magnetic field (total field and component along the GSM Z axis) as well as the latitude and longitude angles $\theta$ and $\phi$ of this field, measured by Imp 4 at a distance $Z'$ from the expected position of the neutral sheet. We do not reproduce the simultaneous variations of the $AE$ index already extensively discussed by Fairfield and Ness [1970]. The first comment about Figure 1 is that there is no apparent correlation between the solar wind energy densities (kinetic or thermal) and the amplitude of the tail field.

Rostoker [1968] has shown that the direction of the interplanetary field in the solar equatorial plane might have an influence on the substorm activity; consequently for the examples presented here we checked this direction (however, it did not change very much so we did not have it plotted). On February 13 between 1100 and 2100 UT the longitude angle remained between 90° and 180° (0° is toward the sun, 90° along the dusk meridian, 180° away from the sun, etc.).

In Figure 2 the variation versus time of the solar wind magnetic field orientation, the ground
magnetic activity, and the increases or decreases of the tail field are shown schematically. We shall use the same format for all examples and it is worth discussing in some detail. In regard to the solar wind data presented on the left we represent differently the time intervals where the orientation is southward (S), northward (N), or horizontal (with or without fluctuations). In the tail data shown at the right, we represent the time intervals with slow increases or decreases of the field with vectors of appropriate slope. The rapid decreases (increases) considered to be due to the expansion (thinning) of the plasma sheet are indicated by 'expans. (thinning). The magnetic activity measured from the ground observatories and

Fig. 1. Variation versus universal time of the solar wind (Explorer 33) and magnetotail (Imp 4) data. (Top) the solar wind kinetic energy density and thermal energy density as well as angle $\alpha$ between the solar wind magnetic field and the ecliptic plane. (Bottom) the magnetotail total field $F$ and component of this field along the $Z$ GSM axis; $\theta$ and $\phi$ are the usual latitude and longitude angle of the tail field. $Z'$ is the distance between Imp 4 and the expected position of the neutral sheet. The magnetotail data [Fairfield and Ness, 1970] and the solar wind data have been shifted by 20 min relative to each other. This time delay is required to convey any solar wind perturbation along the 90 $R_E$ between Explorer 33 and Imp 4.
Fig. 2. Sketch of the association between the solar wind magnetic field orientation (S indicates southward, N indicates northward), the existence of substorms (each isolated sequence of substorm is delineated by a dashed line; EP indicates the onset of the expansion phase), and the variation of the tail total magnetic field (’Expans’ and ‘thinning’ refer to the rapid decreases or increases of this field considered to be due to the expansion or thinning of the plasma sheet; the shaded areas correspond to the slow increases or decreases of the total field). The oblique lines in this position-versus-time reference system represent the propagation of the solar wind perturbations from Explorer 33 to the earth and Imp 4. At the bottom the projection of the various satellites in the $XY_\text{SS}$ plane is shown. For the ATS 1 orbit, universal time at the beginning and the end of the orbit are indicated.

The ATS satellite is shown in the center: each substorm sequence from the growth phase until the end is delineated by dashed lines, and in each sequence the approximate onsets of the expansion phases (EP) are indicated. As the timing of substorm from ground magnetograms can be very controversial, the data from 17 ground observatories used in this study are shown in Appendix A (Figure 10). At the bottom of the figure the relative positions of the satellites Explorer 33, Imp 4, and ATS 1 are shown by projections on the GSE equatorial plane. On February 13 Explorer 33 was about 65 $R_e$ in front of the earth and Imp 4 was about $-25 R_e$. 

behind the earth. The relative spacing in Figure 2 of the vertical lines labeled Exp. 33, earth, and Imp 4 reproduces this configuration. We used the velocity of the solar wind as measured by the M.I.T. plasma experiment on board Explorer 33 (hourly averages 480 to 515 km/sec during this time interval) to trace the trajectory of any reversal of the interplanetary field from Explorer 33 to the earth and Imp 4; the oblique lines in Figure 2 represent such a trajectory when the decrease in velocity behind the bow shock is neglected.

It appears from Figure 2 that the tail magnetic field far from the plasma sheet ($Z'$ is larger than 6 $R_s$) increases slowly when the interplanetary field turns southward (around 1100 UT), or horizontal with fluctuation (around 1410 UT) and that it decreases slowly following (without more precision) the onset of the expansion phase of substorms (around 1230 and 1610 UT). It should be emphasized that these slow decreases of the field start roughly coincident with substorm expansion and precede the change in solar wind magnetic field, thus establishing the association of this effect only with substorms.

February 14, 1968; rapid changes in tail field. Figure 3 presents the original data for this event in the same format as discussed for Figure 1. In regard to the solar wind magnetic field orientation a word of caution is necessary. The Ames magnetometer was at this time working in 'error mode' and measured 'instead of the total vector, one half of the vector component lying in the spin plane' [Colburn, 1969]. Thus the angle $\beta$ in Figure 3 is different from the angle $\alpha$ in Figure 1, but as the spin plane of Explorer 33 is normal to the ecliptic plane, both angles have the same sign and a negative (positive) $\beta$ angle means a southward (northward) interplanetary magnetic field. Owing to this error mode, the longitude of the interplanetary magnetic field could not be measured. Figure 4 presents schematically the variation of the solar wind magnetic field orientation, ground magnetic activity, and amplitude of the tail field by using the same format as in Figure 2.

The event of February 14 shown in Figures 3 and 4 has been selected because it provides a sharp contrast to the two slowly varying events of February 13. A sudden increase in field magnitude at 2120 and a sudden decrease at 2350 are the distinguishing features of this event. From Figure 3 there is again no obvious correlation between the solar wind kinetic energy and thermal energy density and the tail field. The convection velocity of the solar wind 410 to 470 km/sec during this time interval was used to draw the oblique lines in Figure 4. As already noted by Fairfield and Ness [1970], the interplanetary field remained northward from 0300 till 2000 UT; during this time there was no magnetic activity on the ground, and the tail data show that from at least 0600 UT (Figure 3) Imp 4 remained in a thick plasma sheet. Accordingly the diagram in Figure 4 has been limited to the interval 2000 to 2400 UT. It appears from Figure 4 that the rapid increase of the magnetic field at 2120 followed the reversal of the interplanetary field from northward to southward. The rapid decrease at 2350 UT followed a reversal from south to north. Between 2130 and 2400 UT weak magnetic activity was recorded on the ground; however, no distinct substorm expansion could be identified, (Figure 11). The increased stability of the field between the times of the rapid increase and decrease suggests that Imp 4 was in the lobe of the tail rather than the plasma sheet. Furthermore, it should be emphasized that the rapid increase and decrease of the field occurred at rates of about 0.5 $\gamma$ per min in contrast to a rate of less than 0.1 $\gamma$ per min on February 13 (Figure 1), when Imp 4 was definitely in the lobe. Because these rates are so much greater than those characteristic of the lobe we attribute the sudden changes to passage through a spatial boundary, i.e., the boundary of the plasma sheet. Furthermore, since no distinct substorm could be identified in the ground data we conclude that the thinning of the plasma sheet at 2120 and the expansion at 2350 UT were responses to the direction of the interplanetary magnetic field rather than substorm activity.

An additional example of this same phenomenon occurred at 1810 on February 13 (Figure 1). A sudden decrease in field magnitude and a sudden appearance of turbulence in the field indicate that Imp 4 was engulfed in an expanding plasma sheet. Ground magnetograms, Figure 10, show that no substorm expansion occurred at this time. However, the solar wind data show that the interplanetary
magnetic field did switch northward. The plasma sheet after 1800 UT (Figure 1) was about 18 $R_e$ thick.

In summary, from the observations of rapid changes on February 13 and 14 we conclude that the plasma sheet thins when the interplanetary field turns southward and expands when it turns northward.

March 28, 1968. We chose this event because it is a good example of the most typical signature in the tail at the time of substorms: namely a combination of a slow increase before the substorm and a sharp decrease after the substorm. Figure 5 presents the solar wind data as before. During this same interval the longitude of the interplanetary magnetic field fluctuated between 270° and 320°. From Figure 5, no correlation appears between the variation of the tail field and the variation of the solar wind plasma parameters. In Figure 6 the sequences of events in the solar wind, the magnetosphere, and the magnetotail are represented schemati-
cally in the usual way; the ground magnetograms are shown in Figure 12. In Figure 6 we observe the classical features already described for the data from February 13 and 14, namely the tail field increases slowly when the solar wind magnetic field turns southward (0330 UT) and the plasma sheet expands when the solar wind magnetic field turns northward (0420 and 0800 UT). At 0650 UT we cannot determine which part of the field variation at Imp 4 is due to the crossing of the border of the plasma sheet and which part is truly a temporal increase.

For March 28 we have additional information provided by the UCLA magnetometer on the Ogo 5 satellite outbound in the dawn meridian between 9.5 and 16.5 \( R_E \) (see bottom of Figure 6). These Ogo 5 data will enable us to present an over-all view of what is occurring simultaneously in the solar wind, the far magnetosphere at dawn (Ogo 5), the inner magnetosphere at dusk (ATS 1), and the tail at \(-30 R_E\) (Imp 4). In Figure 7 the ATS 1 and Ogo 5 data are presented versus universal time. At the very top the orientation of the solar wind magnetic field (south or north) is indicated schematically; vertical lines allow one to visualize the possible effect of the solar wind magnetic field reversals and of the onsets of substorm expansion phases on the various parameters. For the ATS 1 data, panel 1 shows the deviation of the total field from the dipole field and panel 2 shows the total rms fluctuations. Below, the Ogo 5 data are represented in the same manner used by Russell et al. [1971]: the difference between the measured and the expected field [Jensen and Cain, 1962], the rms fluctuations, the inclination (the angle of the field with respect to a plane perpendicular to a radius vector through the satellite; this angle is positive when the field points be-

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**Fig. 4.** Sketch of the association between the solar wind magnetic field orientation, the existence of substorms, and the variation of the total magnetic field in the tail. For further details see the legend of Figure 2.
low this plane), the declination (the angle between the projections in this same perpendicular plane of the north dipole and observed field), and finally the $B_z$ (GSM) component of the measured field.

Three types of information drawn from the Ogo 5 data are shown schematically in Figure 6. Between 0300 and 0720 UT Ogo 5 was in the magnetosphere and measured a positive declination (see Figure 7). This is the distortion expected for a swept back field line. We shall associate the changes in this distortion with changes in the solar wind and the tail magnetic field, as well as with the substorms. At 0720 UT Ogo 5 crossed the magnetopause and we note that the magnetosheath field was indeed southward. After 0720 Ogo 5 recorded successive positions of the expanding magnetopause. Let us first comment on this expansion of the magnetopause.

The first of three main magnetopause crossings occurred at 0720 UT. The position of Ogo 5 in GSM at this time was $X = 0.5$, $Y = -11$, $Z = +8$ (in earth radii), i.e., at high latitude on the dawn meridian. A second crossing occurred around 0830 ($X = 1.1$, $Y = -11.7$, $Z = 9.0$), and the last crossing (not shown in Figure 7) was recorded at about 1020 UT ($X = 2.0$, $Y = -12.7$, $Z = 10.1$). The geocentric distances $D$ of these three main crossings are indicated in Figure 6. Although there were considerable magnetic fluctuations and multiple crossings during this time interval, the solar wind plasma experiment on board Ogo 5 shows that the outbound Ogo 5 satellite was indeed in the magnetosheath from 0720 until about

Fig. 5. Variation versus universal time of the solar wind (Explorer 35) and magnetotail (Imp 4) data. For further details see the legend of Figure 1.
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0830 UT, and then in an expanding magnetosphere from 0830 until 1020 UT. After this time it definitely entered the magnetosheath (Neugebauer, personal communication, 1970). It appears that, starting some time before 0830 UT, the geocentric distance of the magnetopause on the dawn meridian increased from 13.8 to 16.5 Rs in less than 2 hours.

We may comment now on the observations made by Ogo 5 and ATS 1 inside the magnetosphere prior to 0720 UT. From Figure 7 the most variable parameter as measured by Ogo 5 was the declination that represents the twisting of the field line out of the dipole meridian. The average rate of variation of this angle in degrees per hour can be measured by using the dashed lines in Figure 7, and these rates after 0330 UT are indicated schematically by cross-hatching in Figure 6. Owing to the many sources of information available on March 28, 1968, we

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Fig. 6. Sketch of the association between the solar wind magnetic field orientation, the existence of substorms, and the variation of the total magnetic field in the tail. Some data from Ogo 5 in the dawn meridian are shown schematically: namely the rate of change of the declination angle before 0720 UT, the orientation (southward) of the magnetosheath field from 0720 to 0800 UT, and the various magnetopause positions recorded by the satellite. For further details see the legend of Figure 2.
Fig. 7. Variation versus universal time of the magnetic field at ATS 1 and Ogo 5 on March 28, 1968. From the top: the orientation of the solar wind magnetic field (S indicates south, N indicates north) as it would be observed at the distance of the earth; the difference $\Delta B$ between the total fields measured and expected at ATS 1 as well as the rms fluctuations (3) of the measured field; these two same quantities $\Delta B$ and (3) for Ogo 5; the inclination, declination and vertical component $B_z$ (GSM) of the field at Ogo 5. Vertical lines point the influence of the solar wind magnetic field orientation and of the substorm expansion phases on these various parameters. The vertical line at about 0640 UT when there is no solar wind data correlates with the beginning of the increase in the depression at ATS 1 and the declination at Ogo 5.
shall present a chronology of the two sequences of events from 0330 to 0500, and from 0630 to 0900 UT. The accuracy of these chronologies is not claimed to be better than a few minutes. In each sequence the events are grouped in three sets A, B, and C associated with the reversal of the interplanetary field to southward, or northward, or with the substorm activity. The indicated times of arrival of the solar wind refer, the first, to the arrival at the dawn dusk meridian, and the second, to the arrival at 30 $R_e$ behind the earth. As explained above, the slowing down of the solar wind flow behind the bow shock is neglected and that is why we use the expression ‘predicted earliest time . . . ;’ we refer to the ATS I observations as ‘dusk (6.6 $R_e$)’ observations and to the Ogo 5 ones as ‘dawn (10 $R_e$)’ observations.

First Sequence

A. 0322–0330: predicted earliest time of arrival of the southward interplanetary field. 0330–0335: increase in the rate of change of the field depression at dusk (6 $R_e$) and of the field declination at dawn (10 $R_e$); onset of increase in the tail field magnitude at $-30 R_e$. 0335: onset of magnetic noise at dusk (6 $R_e$); onset of a substorm expansion phase at Great Whale River (local time about 2230). (Not shown in Figure 7.)

B. 0410–0420: predicted earliest time of arrival of the northward interplanetary field. 0410: the declination stops increasing at dawn (10 $R_e$). 0416–0418: drop of the field at $-30 R_e$ interpreted as an expansion of the plasma sheet. Note that this is more than 10 min before the onset of the substorm expansion phase. 0415: second rapid increase in the depression at dusk (6 $R_e$), (note that between 0400 and 0430 a very irregular recovery phase is in progress at Great Whale River, Figure 12).

C. 0430: onset substorm expansion phase at Great Whale River (local time about 2330). 0434: $B_z$ begins to increase at $-30 R_e$ into the tail. 0437: $B$ total (F in Figure 5) begins to decrease at $-30 R_e$ into the tail. 0430–0440: at dusk (6 $R_e$) onset recovery; at dawn (10 $R_e$) beginning of the return of the magnetic field toward the dipole configuration (the main change is in the declination) and arrival of $>40$-kev electrons (M. Kivelson, personal communication, 1970). Note that these changes did not occur at the reversal of the interplanetary field (0410–0420) but only after the onset of the substorm expansion phase. 0448: end substorm expansion phase at Great Whale River.

Second Sequence

A. 0640: increase in the rate of change, of the field depression recorded by ATS I at 2100 LT (6 $R_e$) and of the field declination recorded by Ogo 5 at dawn (13 $R_e$). Onset of the increase in the tail field (as Imp 4 is not in the main lobe at the beginning, this increase is probably partly due to a thinning of the plasma sheet). (Note that the solar wind data are missing at this time, but at 0720 UT Ogo 5 reached the magnetosheath where a southward magnetic field is recorded.)

B. 0650: onset expansion phase of a substorm at Great Whale River (about 0200 LT). 0707: recovery at 2100 LT (6 $R_e$) simultaneous with the onset of a recovery in $H$ at Fredericksburg (about 0200 LT). This is the time selected for the vertical line in Figure 7. 0750–0800: drop of the field at Imp 4 interpreted as a crossing of the plasma sheet border.

C. 0752–0758: predicted earliest time of arrival of the northward interplanetary field. 0802: observed time of change of orientation of the magnetosheath field (southward to horizontal) at dawn (Ogo 5). That is why the vertical line corresponding to the reversal in Figure 7 is drawn between 0800 and 0810. 0815: first partial magnetopause crossing showing that the magnetosphere boundary is getting disturbed at Ogo 5. 0830: the magnetopause at dusk has begun to move outward. 0833: the plasma sheet expansion reaches 6 $R_e$ from the neutral sheet at a distance of $-17 R_e$ (Vela 4A; Akasofu et al. [1970]).

A remark can be made about the crossing of the plasma sheet border at 0750 by Imp 4. The expansion phase of a substorm was in progress at Great Whale River from about 0700 until 0812 UT. The crossing of the plasma sheet border occurred too early (by about 10 min) to be explained by an expansion due to the solar wind magnetic field change. As this crossing occurred at only 0.3 $R_e$ from the expected position of the neutral sheet, we suggest that it was a crossing of a motionless (or slowly moving) border, the real expansion beginning.
about 10 min later at the arrival of the change in the interplanetary magnetic field (about 0805 if we note that the change in the field orientation occurred at 0802 in the dawn magnetosheath) and reaching Vela 4 after about 30 min (20 km/sec).

From these two sequences we want to emphasize that: (a) the action of a southward field is to increase the tailward distortion of the line of force in the far magnetosphere at dawn, to depress the magnetic field at a geostationary orbit (nightside), to increase the tail field (and to thin the plasma sheet); and that (b) the action of a northward field is to expand the plasma sheet.

The asymmetry of these two effects is obvious: the magnetic field in the magnetosphere does not return to its normal configuration when the interplanetary field turns back to northward, and the paragraph C in the first sequence shows that this return to dipole occurs through a substorm.

Let us note that an expansion of the dawn magnetopause (about 2 Rs in 2 hours) is observed to follow at about 0830 UT the reversal of the interplanetary field to northward.

Discussion and conclusion. We have shown examples of slow and rapid variations of the tail field at about 30 Rs behind the earth at the time of change in the interplanetary magnetic field orientation. If we assume that the slow variations are temporal and the rapid ones are due to the crossing of the plasma sheet boundary, then we can summarize our observations as follows.

The tail magnetic field increases slowly when the interplanetary field is southward or horizontal with fluctuations; on two occasions (March 28) the Ogo 5 data show that this is accompanied in the dawn meridian by a rapidly increasing distortion of the magnetic field wherein field lines are increasingly swept back with respect to a magnetic meridian plane. The tail magnetic field decreases slowly in association with substorms.

The plasma sheet thins rapidly immediately following a reversal of the interplanetary field from north to south, and expands immediately when the interplanetary field turns northward.

These results are not based on any statistical study; moreover, at some times the magnetic field in the tail does not seem to react as expected (for instance, the plasma sheet expansion that should occur on February 14 at 2220 UT is not observed); whether this is due to the position of the satellite at this time or to some other cause we cannot determine. Additionally we are aware that the near tail magnetic field can also depend on other solar wind parameters such as the kinetic energy density and the longitude angle of the interplanetary field; our analysis and our conclusions are limited to situations when these other parameters remain roughly constant (and assuming sufficiently large kinetic energy density and a longitude angle different from zero, namely, an interplanetary magnetic field not pointing toward the sun). We shall now discuss these results and compare them with those of other authors.

Temporal or spatial character of the slow increases of the tail magnetic field. Lazarus et al. [1968] have reported a situation where the tail magnetic field increased and decreased slowly and have shown that the total pressure increased and decreased slowly with the field. In contrast they have interpreted as rapid spatial variations (crossing of a border) situations where the pressure remained constant when the field varied. Consequently in keeping with this philosophy we prefer a temporal interpretation of the slow variation. However, an important problem remains unsolved: even assuming that these temporal variations are due to an increase of the pressure of the solar wind on the near tail through an increase of the flaring angle it remains difficult to explain their amplitude. Indeed, in a previous paper [Aubry et al., 1970] evidence was presented for a flux transfer of

Fig. 8. (Opposite). Diagram of the two different sequences of events in the magnetosphere associated with the southward or northward orientations of the solar wind magnetic field. The white lines correspond to purely magnetospheric regimes when the solar wind magnetic field does not change. The dark lines show how the reversals of the vertical component of this solar wind magnetic field allow the magnetosphere to switch randomly from one regime to the other (the vertical positions of the points A and B are arbitrary). Except for the vertical component of the interplanetary magnetic field it is assumed that everything remains constant in the solar wind (V \(\sim\) 400 km/sec, N \(\sim\) 5 cm\(^{-3}\), B \(\sim\) 5\(\gamma\), and oriented away from the sun).
**SUBSTORM RELATION TO THE INTERPLANETARY MAGNETIC FIELD**

1. **Depression ATS**
   - Tailward orientation of the field at dawn
   - Increase of the tail field (main lobe)
   - Thinning plasma sheet

2. **Onset substorm expansion phase**
   - Temporary plasma sheet expansion
   - Temporary dipole configuration at ATS, dawn and tail
   - Decrease of the field main lobe

3. **IMF turns southward**
   - High drag #1 erosion dayside

4. **IMF remains southward**
   - IMF turns northward or horizontal

5. **IMF turns southward**

6. **Low drag #2**
   - Plasma sheet expands; depending on the energy stored, occurrence or not of a substorm

7. **End substorm activity?**
about $10^{16}$ Mx from the eroded dayside to the tail; during this same event the Imp 4 magnetometer recorded a tail field increase from 15 to 24 $\gamma$, which, if occurring uniformly throughout a 20-$R_s$ radius tail, implied an increase by $4.5 \times 10^{16}$ Mx of the tail flux. So although the erosion of the dayside as reported in this paper was fairly dramatic, the flux transfer was lower than $4.5 \times 10^{16}$ Mx and could not account for a uniform increase of the tail field. On February 13 the increase of the tail field from 20 to 30 $\gamma$ between 1400 and 1600 UT (Figure 1) implies the same difficulty. We do not mean that our estimates of the flux transfer are very accurate; we want only to point out that a model in which the flux removed from the dayside is distributed uniformly in the whole section of a tail of constant radius may be oversimplified; it seems quite probable that the slow increases in tail field, if they are purely temporal, either depend on the distance from the neutral sheet or are enhanced by a simultaneous decrease of the radius of the tail. We presently have no arguments to rule out an interpretation in terms of a mixture of spatial and temporal variations.

Temporal or spatial character of the slow decreases of the tail magnetic field. Hones et al. [1970] have shown that the particle pressure in the plasma sheet can decrease by a factor of 2 during a substorm. This observation and the one by Lazarus et al. [1968], showing a slow decrease of the tail magnetic field and total pressure after a substorm expansion, support our interpretation that the slow decrease is temporal. As for the slow increase discussed above, however, we cannot rule out the possibility of a mixture of spatial and temporal variations.

Thinning of the plasma sheet following a reversal of the interplanetary field turning southward. One more example of this phenomenon can be found in Hones et al. [1970]. They report that on August 25, 1967, the satellites Vela 3A and 4A ($X_{ss} \sim -18 R_s$) recorded the plasma sheet thinning from 2215 UT with a velocity of about 6 km/sec. We checked that at Explorer 33 ($X_{ss} \sim 10 R_s$, $Y_{ss} \sim 12 R_s$) the interplanetary magnetic field turned slowly southward after 2124 UT and was 90° southward after 2218 UT (data not shown).

Expansion of the plasma sheet following a reversal of the interplanetary field turning northward or a substorm. In the examples presented above there was quite often no substorm activity to account for the observed expansion, so we think that this relation between the expansion and the arrival of the northward interplanetary field is well confirmed. For instance, on February 13 at 1810 UT (time of the expansion) the recovery phase of the substorm is nearly finished and on February 14 there is only a very weak ground disturbance during the interval 2100–2400 UT. However, it is obvious that substorms themselves can trigger expansions of the plasma sheet. As a confirmation of this, recall that Hones et al. [1970] presented evidence for plasma sheet expansion after the onset of the substorm and before the reversal of the interplanetary field to northward. Examples of rapid variations of the tail field associated with substorm expansion onset have been presented by Camidge and Rostoker [1970] and Brody and Holzer [1970]. (See Figure 3 in the second paper).

Quite often, however, it is impossible to separate the contribution of the substorm and of the interplanetary field reversal to the plasma sheet expansion. At other times the influence of the substorm and of the interplanetary field reversal could be contradictory; this could explain the tail signature observed on March 27, 1968, at 0740 UT [Aubry et al., 1970; Figure 5]. At this time an expansion of the plasma sheet occurred in association with the onset of a substorm and with the reversal of the interplanetary field turning southward.

Expansion of the dawn magnetopause following a reversal of the interplanetary field turning northward. This phenomenon was observed on March 28 after 0800 UT. We do not know if a large part of the magnetopause was involved, and it is not clear if the plasma sheet expansion observed by Vela 4A at 0833 UT [Akasofu et al., 1970] and this local magnetopause expansion are part of a global expansion triggered by the arrival of a northward interplanetary field. But, as in an earlier paper [Aubry et al., 1970], we emphasize the large changes in the magnetopause position occurring under quiet solar wind plasma conditions.

The indirect dependence of the tail characteristics on the solar wind through the substorm process has been shown by many authors
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[Heppner et al., 1967; Hones et al., 1967, 1968, 1970; Lazarus et al., 1968; Hones, 1969; Akasofu et al., 1970; Fairfield and Ness, 1970; Brody and Holzer, 1970; Meng and Anderson, 1970; Camidge and Rostoker, 1970]. We have shown in this paper that the tail characteristics also depend directly on the interplanetary field, and that the tail at 30 Rs reacts immediately to the changes in the motion electric field (V × B) associated with changes in the solar wind magnetic field orientation. In particular we have shown that the slow increase in tail field and thinning of the plasma sheet systematically reported before substorms are produced by the arrival of a southward interplanetary field. We have also shown that the highly variable correlation between substorms and plasma sheet expansions is due to the fact that these expansions are frequently produced by the arrival of a northward solar wind magnetic field.

It would be unfair to claim that we understand each intermediate step in this picture. Some of the most obvious problems are: what are the relative importance of spatial and temporal variations in the slow increase and decrease of the tail field; and, although we claimed that the tail reacts 'immediately' to the change in solar wind orientation, imprecisions of various kinds limit severely the accuracy of our timing (a brief discussion of this problem is given in Appendix B).

However, from the simultaneous observations by several satellites presented above, we can infer a gross picture of the relations between the changes in the solar wind magnetic field orientation and the changes in the magnetosphere and the magnetotail before and after substorms (Figure 8). First we must assume that, except for the vertical component of the interplanetary magnetic field (IMF), everything remains constant at some reasonable average value in the solar wind (velocity ~ 400 km/sec, density ~ 5 cm⁻³, B ~ 5 γ), and to avoid the longitude effect reported by Schatten and Wilcox [1967] and Rostoker [1968] we do not consider situations where the interplanetary magnetic field is directed exactly toward the sun.

On the left of Figure 8 the sequence of events following the onset of a southward IMF is presented schematically. The high drag and the erosion of the dayside have been reported by Aubry et al. [1970]. The other effects in the magnetosphere and in the magnetotail (box 1) are those reported above; by the 'tailward orientation of the field at dawn,' we mean the rapid increase in the declination as shown in Figure 7. These changes (in box 1) as well as the beginning of the increase in the AE index as shown by Fairfield and Ness [1970] are a part of the substorm growth phase. Some time later the substorm expansion phase starts and some of its consequences are listed (in box 2).

If the IMF remains southward a closed loop of events is set up (white line), the substorms being the only way to release the stress imposed on the magnetosphere by the southward IMF. Such a closed loop in fact can lead to a magnetic storm. Such an event occurred on February 11, 1968, between 0300 and 0900 UT. Fairfield and Ness [1970] show the successive thinning and expansions of the plasma sheet (see their Figure 9). Our examination of Explorer 33 and 35 magnetometer data (not shown) indicates that the IMF remains southward during this interval. (However, one must note also that the IMF amplitude was over 10 γ and that the density of the solar wind varied between 10 and 17 cm⁻³).

If the IMF turns northward the sequence on the right is set up. Depending on the energy stored in the magnetosphere and tail before the reversal, a substorm can be observed at this LOCATION OF MAGNETIC OBSERVATORIES GEOGRAPHIC-NORTH POLAR PROJECTION

Fig. 9.
time, but from our very limited observations (February 14, 1968, before 2100 UT, Figure 3) and from statistical studies it seems that the substorm activity should end rapidly [Rostoker and Fälthammer, 1967; Schatten and Wilcox, 1967; Zelwer et al., 1967, Rostoker, 1968]. When the vertical component of the IMF reverses the magnetospheric sequence switches from one regime to the other (dark lines); since this can happen at anytime in the sequence, this means that the vertical positions of the points A and B, origin of the dark lines, are arbitrary.

Consequently, when the time interval between the IMF reversals is smaller than the 'time constant of the magnetosphere' (time constant of the loop on the left, for instance) one never observes a simple magnetospheric sequence (left or right), but parts of the sequence on the left and parts of the sequence on the right combined randomly by the reversals of the interplanetary magnetic field.

The main consequence of this statement is that for any future studies of magnetospheric dynamics it becomes imperative that simultaneous measurements be made of the parameters of the solar wind (reasonably close to the earth), the near tail (<50 Rs), and the magnetosphere. We have shown that the data presently available are adequate to begin this study.

APPENDIX A

To support the magnetospheric substorm pattern sketched in Figures 2, 4, and 6, we show in this appendix the ground magnetograms of 17 magnetic observatories. Their position at 0000 UT is shown in Figure 9. In Figures 10, 11, and 12 the deviation of the H component from the quiet day trace is shown for each of these stations. It should be noted that photographic reduction of Figures 10, 11, and 12 invalidates the indicated scale. One inch corresponds to 2 hours on the horizontal axis.

The names of the stations are, from the top:

SO, Sodankyla
LR, Leirvogur
GW, Great Whale River
ME, Meaook
SI, Sitka
CO, College
SJ, San Juan
FR, Fredericksburg
DA, Dallas
TU, Tucson
HO, Honolulu
GU, Guam
KA, Kakioka
GN, Gnangara
TA, Tashkent
MR, Hermanus
MB, M'Bour

APPENDIX B. TIMING OF THE REVERSALS OF THE SOLAR WIND MAGNETIC FIELD

We have made the simple assumption that the changes in solar wind magnetic field orientation convect from the observing spacecraft to the magnetosphere with the solar wind velocity. It can be argued that this is a very rough approach: first, we have neglected the slowing down of the plasma flow behind the bow shock; second, we do not know the orientation in space of the border between the regions of northward and southward interplanetary field, and the real time of arrival of the perturbation at the earth depends on this orientation and on the position of the satellite in the solar wind; third, there is no one time of arrival, but an interval of time during which the new orientation of the interplanetary field is felt by larger and larger portions of the magnetopause. For instance the dawn and dusk meridian can be reached at different times; when this occurs, we use the latest time and we label it 'time of arrival at the earth.' In regard to the second problem it can be easily shown that the real convection time from the satellite to the earth (see definition above) can be written, in the three examples presented below.

\[ \Delta t = \frac{X_s}{V_{sw}} + \frac{Y_s + 20R_s}{V_{sw} \sin \gamma} \]

where \((X_s, Y_s)\) is the spacecraft position in GSE \((X_s > 0, Y_s < 0)\), \(V_{sw}\) is the solar wind velocity, and \(\gamma\) is the angle (between 0° and 90°) of the border between southward and northward field (assumed to be a plane parallel to \(Z_{gas}\) and the \(ZX_{gms}\) plane; the magnetosphere is assumed to be 40 \(R_s\) wide. The first term on the right is the time delay used in our analysis. The second term would be zero for February 14 \((Y_s \sim -20 \ Rs)\). If one assumes \(\gamma = 45°\) (roughly the firehose direction) and
\[ V_{sw} = 500 \text{ km sec}^{-1} \] this second term would be 
-2 min for February 13 (\( Y_\gamma \sim -30 R_s \)) and 
+2 min for March 28 (\( Y_\gamma \sim -10 R_s \)). These 
errors are not important for our analysis. It is 
not our purpose to discuss the other possible 
configurations (\( \gamma \) between 90° and 180° or 
\( Y_\gamma < 0 \)). This would be straightforward. It is 
obvious that if \( \gamma \) becomes small the second 
term can be very large even when \( Y_\gamma \) is small. 
The only easy way to deal with this problem 
is to consider that such small \( \gamma \) should not be 
typical and accordingly to avoid drawing con-

Fig. 11.
clusions from an isolated observation. Thus in the discussion we have emphasized similar observations made by other authors or the fact that we observed the same behavior on different days (for instance, the expansion of the plasma sheet following a reversal of the solar wind magnetic field to northward).

Note added in proof. Our recent studies of the tail behavior at 10 to 15 Rs show no striking evidence for plasma sheet expansion triggered by changes in the solar wind magnetic field orientation but a much greater sensitivity to substorms. This confirms and extends the Ogo 5 observations on March 28 and implies that the tail behavior depends very much on the distance from the earth.

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